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Modeling the OH-6A using FLIGHTLAB and helicopter simulator considerations

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THESIS

MODELING THE OH-6A USING FLIGHTLAB AND HELICOPTER SIMULATOR CONSIDERATIONS

by

Gregory A. Ouellette

March 2002

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Recent technological advancements in robust computer hardware, simulation modeling technology, newer electronic actuators and advanced computer graphics have enabled manufacturers to develop low cost, affordable helicopter flight simulators. This thesis presents detailed information on the U.S. Army Hughes OH-6A "Cayuse" helicopter together with a comprehensive model of the aircraft suitable for high fidelity simulator modeling. Fidelity of the model is obtained through use of commercial off-the-shelf software that is incorporated in a low-cost flight simulator, which is marketed as FLIGHTLAB. The FLIGHTLAB development system facilitates rapid design and analysis of a high fidelity helicopter model using non-linear dynamic modeling techniques. The simulator model of the Hughes OH-6A helicopter is presented and its fidelity is compared to actual fight test data conducted at the U.S. Naval Test Pilot School in Patuxent River, MD. Advancements in electromagnetic actuators and visual rendering systems are also presented to provide insight into the direction simulator technology is progressing.

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MODELING THE OH-6A USING FLIGHTLAB AND HELICOPTER SIMULATOR CONSIDERATIONS

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Submitted in partial fulfillment of the
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Recent technological advancements in robust computer hardware, simulation modeling technology, newer electronic actuators and advanced computer graphics have enabled manufacturers to develop low cost, affordable helicopter flight simulators. This thesis presents detailed information on the U.S. Army Hughes OH-6A "Cayuse" helicopter together with a comprehensive model of the aircraft suitable for high fidelity simulator modeling. Fidelity of the model is obtained through use of commercial off-the-shelf software that is incorporated in a low-cost flight simulator, which is marketed as FLIGHTLAB. The FLIGHTLAB development system facilitates rapid design and analysis of a high fidelity helicopter model using non-linear dynamic modeling techniques. The simulator model of the Hughes OH-6A helicopter is presented and its fidelity is compared to actual fight test data conducted at the U.S. Naval Test Pilot School in Patuxent River, MD. Advancements in electromagnetic actuators and visual rendering systems are also presented to provide insight into the direction simulator technology is progressing.

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I. INTRODUCTION

A. BACKGROUND

The Naval Postgraduate School (NPS) was the recipient of two OH-6A "Cayuse" helicopters from the Massachusetts Army National Guard in 1995 as they transitioned to using the UH-60A "Blackhawk". Several analyses have been conducted on these helicopters including a 1996 experiment carried out by LT John Harris (Ref 1.1) who performed a preliminary vibrations study to identify fuselage natural frequencies and mode shapes. His results were compared to prior "shake" test data of the OH-6A conducted at NPS and McDonnell Douglas Helicopter Company (MDHC). In 2000 NPS shipped one of the helicopters to Mississippi State University to be refurbished back to flight condition and for use in in-flight experimentation at the University's rotorcraft center. Also in that year, NPS signed a Cooperative Research and Development Agreement (CRADA) with Advanced Rotorcraft Technology, Inc. (ART) to mutually develop advancements of rotorcraft technology. Within this CRADA, ART and NPS worked together to develop a basic model of an OH-6A that was displayed at the 57th Annual American Helicopter Society (AHS) Forum in May 2001. NPS provided ART with the sticks and grips, seats, instrument panel and avionics suite of the remaining OH-6A for integration onto the control loader platform while ART provided their helicopter-modeling suite with advanced visual rendering equipment in order to produce a fully functional stationary open platform flight simulator. In return for this equipment, ART provided their flight modeling software (FLIGHTLAB) to NPS to develop rotorcraft models for future use to include the OH-6A and V-22 "Osprey".

This thesis will investigate the current technology built into modern low cost flight simulators. Specifically we will look at: the motion systems visual rendering system and mathematical modeling device used in ARTs full motion flight simulator called HELIFLIGHT II. We will also develop a model of the OH-6A to be used as the mathematical model in a flight simulator

B. TECHNOLOGICAL PROBLEM

Learning to fly a helicopter is a challenge that is complicated by the high degree of freedom that a pilot must control, coupled with prolonged periods of unstable flight which is common to helicopter operations at low-speed. Helicopter simulators provide a risk free environment to augment flight training such as instrument flight, weapons management, cockpit procedures and, most importantly, pilot flight maneuvering.

Operational Flight Trainers (OFT) are simulators that have the required fidelity to support flight training in flight dynamics. The flight dynamics model of the OFT must be accurate and validated against experimental data, the visual displays must be of high enough quality to accurately reproduce the low-altitude/low-speed environment common to helicopter flight and the control loading and motion cues must accurately reflect those of the aircraft. Accomplishing all this has typically been prohibitively expensive. Given the value of simulator training there is a great need for affordable, high fidelity training simulators.

Opportunities to reduce cost and provide affordable helicopter simulators have been aided by recent technological advancements including: (1) robust computer hardware; (2) simulation modeling technology; (3) newer electronic actuators; and (4) advanced computer graphics. Simulator manufacturers have not taken the initiative to integrate these new technologies because the development of helicopter simulators has generally been conducted in response to government procurement and the design specifications often limit the use of creative new technologies. These unique specifications generally do not provide for cost-effective upgrades to new technologies and thus result in early obsolescence. Reusing or interchangeability of simulator technology is prevented by lack of commonality in software, math modeling, and hardware, thus adding to the development and maintenance costs. (Ref 1.2)

C. SIMULATOR TECHNOLOGIES

The primary technology areas involved in producing a helicopter simulator are vehicle mathematical modeling, visual displays, motion platforms, and control loaders. (Ref 1.2) The following describes current practices in these areas:

1. Helicopter Mathematical Modeling

Helicopter flight dynamic models are currently computationally intense, physics-based models tuned to test data and/or pilot evaluation. Consequently, tuning is focused on the acceptance test criteria and the results are valid only at the tuned condition, thus there is no clear-cut way to ensure accuracy of results between test points. The accuracy of current helicopter models is limited to moderate maneuvering for normal flight conditions due to lack of knowledge of the physics associated with certain complex areas of helicopter flight such as vortex ring state. Empirical models like these require customized development for each vehicle and the result is little commonality between different models.

2. Visual Systems

Specialized visual display systems are generally used in the aircraft simulator. These systems typically use specialized hardware to handle the high-speed, computationally intensive requirements of reproducing low altitude displays of highly textured scenes in real-time. The use of specialized visual hardware adds to overall cost of the simulator and makes it difficult to update the system.

3. Motion Base

Motion cues provide the essential signals to a pilot and enhances his control of the helicopter, particularly at low-speed or in a hover. Most motion simulators use hydraulic actuated motion platforms to provide the cues. Hydraulic actuators generally increase the maintenance required and add to overall system costs.

4. Control Loaders

Control forces also aid in providing essential cues to the pilot to facilitate precision control of the helicopter. These cues are different for each helicopter so the control loaders must be software programmable to reproduce the desired force characteristics. Most motion simulators use electromechanical control loaders to provide the control force feedback cues.

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II. MOTION SYSTEMS

A. OVERVIEW

Recent studies show that human beings respond first to tactile disturbances, then later to visual field disturbances when engaged in vehicle guidance control. In other words, visual information is not the primary sensation of control for a human being. Your eyes set targets for your actions but your movement is controlled by feel. Forces are felt as pressures on the skin, the largest and most primitive organ in the body, and your response to these sensations is instantly and instinctively controlled by your subconscious without rational thought to external forces. When we learn to fly an aircraft, we use our fast reactions to body forces to instinctively learn how to blend with the vehicle thus rapidly building an intuitive understanding of where the edges of the vehicle are and what is happening to them. By moving the controls and feeling the results we gain the ability to predict the future position of the vehicle and when it is moving we learn how it interacts with the surrounding medium. The tactile disturbances felt are the complex sum of accelerations that are integrated over time to produce velocities and then integrated again to produce displacements. The displacements alter the visual field but the changes are perceptible later than the body sensations.

B. SIMULATOR MOTION CUES

It is important to note that simulators do not attempt to emulate a real event instead they simulate the event by tricking the human psyche through a combination of visual, aural and motion cues. The key element of simulation is the motion system. The motion system is what sets it apart from a standard video game and adds energy and excitement to the visual experience. The sensations of movement are felt as pressures on the skin, which provoke an irresistible response to react prior to the visual cues.

There are two different types of motion cues, which must be superimposed to generate the motion simulation. The first type results from the interaction of the user to the vehicle such as control movements and can be precisely calculated from the dynamics of the vehicle and coefficients of the controls. The second type are cues resulting from vehicle interactions with its environment such as turbulence or bumps on a runway surface and are generally produced from random variations in the coefficients of interaction between the dynamics of the vehicle and the parameters of the data base that describes the surface with which the vehicle interacts. (Ref 2.1)

Simulators must simulate two different types of accelerations: (1) Gravitational and (2) Inertial accelerations. Gravitational acceleration is caused by the attraction of two bodies while inertial accelerations are produced when we speed up, slow down or turn corners. In an enclosed simulator it is impossible to tell the difference between the two accelerations, thus tricks can be used to simulate the various accelerations. Tilting the platform backwards so that the earth gravity is felt on the pilots back can simulate forward acceleration. Sideways accelerations can be simulated by a roll movement and centrifugal forces can be simulated by combining pitch and roll with gravitational forces. Impulse or changes to acceleration are often more important than sustained acceleration, particularly in combination with visual cues. Use of a technique that apply "onset cues" or short bursts of acceleration followed by a slow reduction in force known as "washout" allows a motion system to effectively work within a relatively small range. (Ref 2.1)

C. HYDRAULICS VS ELECTRICAL

Hydraulic actuators and the technology surrounding hydraulic motion have proven that hydraulics can provide the accuracy and rapid response necessary to create the required sensations of movement in a military aircraft simulator. The hydraulic rams used to create this motion are powerful, precisely machined steel pistons driven by oil under high pressure with the ability to move large masses greater than several tons. The drawbacks to using a hydraulic system to provide the necessary forces is that such systems can be expensive, inefficient (wasting more than 95% of the input power), require cooling facilities and high-power electrical supply, are noisy, need frequent and careful maintenance, and leak oil or spray a fine mist of oil over their surroundings which poses a risk of fire or toxic danger. (Ref 2.2)

There are two obvious alternatives to hydraulic technology: Pneumatics and electric jacks. Pneumatics uses low-pressure air instead of high-pressure oil. The drawback to pneumatics is that its response is slow and imprecise. The ram needs to adjust to a new required pressure which takes time since air is compressible resulting in bounces. Electric jacks use rotary electric motors and speed reduction gears to drive thread shafts and nuts running on ball bearings. The drawbacks to electric jacks are that they are slow to respond or reverse directions because the motors and gears have to spin up or down to start and stop, they are noisy, and they wear out rapidly due to the high constant pressure of the metal surfaces. (Ref 2.4)

Recent advances in linear electromagnetics have produced a silent, compact, DC electromagnetic ram that can produce powerful thrusts with an almost instantaneous response. The electromagnetic ram consists of dual-action linear motors in which a piston moves freely in a cylinder. The piston is part of a gas spring that carries the simulator deadload. The ram is a force generator and not a movement generator like a hydraulic ram. Forces on the piston are continuously monitored such that it only generates the right amount of force to hold the simulator in the required position. This motion base (in contrast to an electromagnetic jack) does not consume power unless it is moving. The electromagnetic ram system is able to work as both a motor and a generator to produce efficiencies greater than 80%. Thus, unlike hydraulic actuators that dissipate the excess energy as heat, the energy produced from the regenerating actuators is transferred to the diametrically opposite actuators that are supplying energy to the payload. This new technology is intrinsically reliable, silent and clean and capable of producing the motion fidelity better than a hydraulic motion base for the same cost. The downside is that hydraulic rams have a significantly higher power density than electrical systems because the hydraulic pressures produced are much higher than the electromagnetic shear stresses in the motor air gap. This makes hydraulic platforms more suitable for high-payload simulators. At moderate payload sizes electrical platform performance is greater than hydraulic systems. The electrical actuators have very high stiffness, which results in virtually no cross coupling between actuators, thus the trajectory of the payload can be controlled more accurately producing higher quality motion cues. Electric actuators also offer better frequency responses with a bandwidth greater than 25 Hz (typically 40-45 Hz) whereas a hydraulic systems bandwidth is typically less than 10 Hz. The main rotor four per revolution vibrations generally occurs between 15-35 Hz and can be achieved using hydraulic or electric actuators. In order for a hydraulic system to develop a higher frequency output, the designer must increase the fluid pressure, increase bulk modulus and/or increase the stiffness of the seals. During the 1982-84 flight tests of Hughes Helicopter's Higher Harmonic Control (HHC) system, engineers were able to produce frequencies up to 100 Hz on three hydraulic actuators using 3000 psi fluid. The three HHC actuators were operated in excess of 25 hours at 32 Hz (4/rev for an OH-6A) and at amplitudes up to 0.2 inches during steady-state flight testing. Frequency sweeps were also conducted between 0-50 Hz for a NASA experiment on the modified OH-6A. While electrical systems can easily reproduce the higher response they require an enlargement of the coil to support a heavy motion platform, which may not be cost effective. For example, current top-of-the-line electromagnetic ram motion systems will support platforms up to 26,000 pounds, yet the design specifications for the MH-60R call for support of platforms up to 30,000 pounds.

D. MOTION PLATFORMS

Motion platforms have been used for many years in the creation of virtual environments. Electric motors were used in the Paris Fair of 1900 to drive ship shaped platform and the pre-WWII Link Trainer was the first flight simulator to use a motion

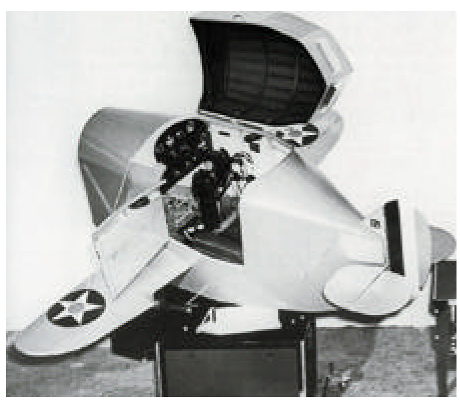

Figure 1: Pre-WWII Link Trainer (From: Ref 2.5)

platform. Motion platforms are characterized by the range of motion, load capacity, degree of freedom (DOF), and type of actuators used. A 1-DOF linear motion system provide only a vibratory sensation such as a "seat shaker". This vibratory sensation is generally produced via acoustic methods today. A 3-DOF platform supports roll, pitch and heave (vertical) motion. Most motion platforms are 6-DOF which support heave, surge (longitudinal) and sway (lateral) linear translations and roll, pitch, and yaw rotational motions. Motion platforms are also classified as "stacked" (motion is carried out independently) or "synergistic" (motion in one DOF automatically limits motion of other kinds). The most common form of a synergistic platform is the "Stewart Platform" or hexapod. This generic configuration consists of a frame with six or more extendable actuators that connect a fixed base to a moveable platform. For example, a lightweight platform system (2,200-3,300 lbs capacity), like the one in Figure 2, uses 6 ft actuators can move small distances (~1 feet) and rotate through small angles (~30°). Heavier motion platforms (30,000+ lbs capacity) use 18 ft actuators that can extend up to 5 feet and rotate through 30°

Figure 2: Stewart-type Platform (From: Ref 2.6)

The greatest limitation of a motion platform is that the only long duration cues that can be presented are lateral accelerations which is produced by tilting the capsule sideways or tipping it up or down resulting in a simulated surge or sway acceleration of up to 0.5 g. All other acceleration cues are of short duration because if the strong force is applied for too long the simulator generates too much speed that cannot be gently arrested prior to the rams hitting their stops thus destroying the simulation illusion.

E. MOTION SEATS

Motion seats or 'g seats' have been developed to provide the illusion of sustained acceleration. Motion seats vary the skin sensations through adjusting the pressures in a matrix of pads forming a harnessed flying seat, thigh restraint and backrest. The greater the force exerted, the greater the increase in hardness of the area of contact. The pilot feels the sensation that he would if the seat were moving against him when in fact the seat hardly moves at all thus duplicating the cues of sustained accelerations as found in high performance aircraft. Early versions of the 'g seat' suffered from a form of latency because it was necessary to physically inflate or deflate the pads, which cause the motion cues to be felt too late to be convincing of the illusion. The seats are designed to react to body movements so that the simulated forces can be continuously felt as the body moves with the motion. Unfortunately the latency of the pads was such that the seat felt like it was moving under the pilot. This tended to destroy the illusion as pilot became aware of the separate seat motion. (Ref 2.1)

Figure 3: 'g seat' (From: Ref 2.7)

Newer, improved sets use miniature dual-action electromagnetic rams to provide the seat pan and backrest motions and to modulate seat belt tension. The resulting seat , with a bandwidth of 100 Hz, is capable of accurately reproducing the vibrations of a helicopter. (Ref 2.1)

F. CONTROL LOADERS

Vehicle handling qualities are highly correlated with stick sensitivity and force gradient. Pilots also utilize control positions and forces as essential motion cues. Control loaders can be either hydraulic or electric. Both will simulate all the springs, linkages, aerodynamic forces and control surfaces of an aircraft. Software can be configured to reproduce the force-feel flight characteristics of the controls of any aircraft. Electric control loaders for the cyclic, pedal, and collective controls provide digital control of the stick gradient and neutral force position allowing the pilot to utilize the force trim release feature to null control forces at the desired trim point. One or more masses are coupled to the pilot's controls through linkage or cable springs. Both spring rate and damping can be varied so that the loader can simulate the changes in force gradient and damping which would occur at a control surface with changes in dynamic pressure.

Hydraulic control loaders are generally controlled via analog electronics that suffer from high levels of maintenance to meet FAA simulator standards and require circuitry redesign and fine-tuning to match changes in the actual aircraft. Analog controllers tend to drift or loose calibration, which requires dedicated maintenance personnel to constantly adjust and realign the controller. Industry has developed ways to bypass all the analog circuitry and drive the hydraulic loaders directly from a PC. This allows for a more maintainable system both in hardware maintenance and engineering requirements. Digital control insures drift free static and dynamic repeatability provides automatic tuning and calibration and provides ample computational capability to ensure superior performance of the hydraulic actuator in achieving any level of certification required

Early electric control loaders suffered from a form of latency, which cause the motion cues to be felt too late. Technological advances in miniature dual-action electromagnetic rams have eliminated the latency effects resulting in control loaders with a bandwidth of greater than 100 Hz and capability of accurately reproducing the vibrations and forces of a helicopter.

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III. VISUAL SYSTEMS

A. OVERVIEW

In the last ten years, improvements in visual simulation technology have had the greatest impact toward increasing the fidelity of flight simulators. Sensor simulation and image generator images are correlated with the synthetic environment so that the pilot perceives all visual cues as part of a cohesive, integrated whole. Visual simulation systems consist of increasingly powerful and affordable image generators, visual simulation software, and display systems.

B. IMAGE GENERATORS

Image generators (IGs) are essentially graphics computers that process the terrain and object model databases and drive the display systems to ensure fully-correlated visual, motion, and real-time responses to pilot actions.

Simulation companies like Evans and Sutherland (E&S) and CAE Electronics Ltd. (CAE) produce high-end IGs for the commercial and military flight simulator market as well as lower end IGs for entertainment purposes such as amusement park rides. High-end IGs can produce a correlating response from a control input to the visual scene (this is called transport delay) in less than 100 msec. The FAA allows for a maximum of 200 msec transport delay in level C and above simulators but test show that pilots can tell down to 100 msec. If a pilot puts in a control input and it takes more than 100 msec for the scene to change his inner ear is sensitive enough to tell the difference and the pilot may then encounter simulator sickness. Some features of a high-end IG include (Ref 3.1):

1. High-quality edge and texturing anti-aliasing, 60 Hz update rate, full color texture, scene management and flicker removal.

2. Realistic dusk and dawn effects that replicate the transition between day and night scenes.

3. Sharp, bright light points that realistically replicate airfield lighting, cultural lighting and star field scenes requiring high-contrast, precise light representation.

4. Clouds that are fully correlated with wind, thunder and lightning visual effects. Realistic, multi-layered, transparent fog and snow that obscure vision in a natural manner. Realistically breaking shoreline waves and dynamic, fully articulated 3-D ocean surfaces.

5. Wind shear, storms, haze, scud, smoke, blowing snow, thunderstorm, runway contaminants and other hazards that are correlated with the appropriate flight effects, radar and sensor systems for high fidelity training under adverse conditions.

C. VISUAL SIMULATION SOFTWARE

The heart of the visual system is a realistic, fully photo-textured, 3D synthetic environment. Synthetic environments are composed of a variety of elements that combine to form a cohesive, realistic out-of-the-window scene. Exceptional levels of realism are achieved by combining geo-specific and geo-typical full-color photo-texture to replicate topographical and cultural features. Surveys, satellite and aerial imagery, on-site photography and digital data provided by the National Imagery and Mapping Agency (NIMA) are all used to generate highly accurate synthetic environments. (Ref 3.2)

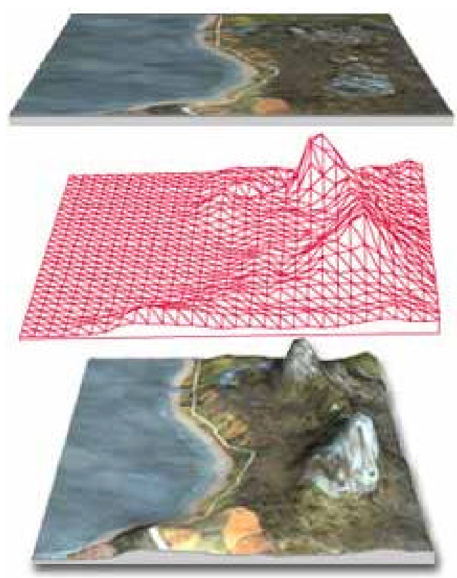

Figure 4: Synthetic Environment Generation (From: Ref 3.2)

Dynamic texturing of realistic effects like blowing snow and moving waves as well as earth curvature effects, star models, sun and moon models, man-made features, weather and air hazards can all be added to each modeled environment to ensure exact duplication of any location.

1. Visual Scene Rendering Tools

Venders like CAE and E&S produce a complete virtual environment toolset that allows database designers to accurately model the world by specifying terrain elevation, topological features, and 3D models. These tools generally use proprietary interfaces and databases and that can be integrated with COTS geographical information system (GIS) and 3D modeling tools like industry standard MultiGen-Paradigm® Creator and ESRI's Arcview™. Visual rendering tools enable designers to quickly and easily produce new visual databases for the latest image generators with minimal modifications to the source data.

In addition, these toolsets incorporate a configuration management system that allows for easy management of visual databases. Visualization tools can help with the analysis of virtual environment content along with automated documentation tools that enable users to obtain statistical information about the database generation process and database content.

D. DISPLAY SYSTEMS

Display systems consist of optical projectors fed by the image generator and projected on display screens. There are three different types of projectors: (1) cathode ray tube (CRT); (2) liquid crystal display (LCD); and (3) laser-based systems. The ultimate goal of the visual systems performance is to have "eye-limited" resolution which means that systems can produce images that match the acuity of the human eye in terms of distinguishing between two small objects. The number of pixels processed by the image generator and the brightness and contrast of the image are key factors affecting resolution. CRT projection systems have improved in recent years, but LCD projectors have gained in popularity because of their much higher reliability, lower life-cycle cost, higher brightness, and lighter weight yet CRT projectors still offer the highest resolution and can produce truer, more vibrant colors. Evans & Sutherland (E&S) is developing a new laser projector that will offer ultra-high resolution, producing up to 32-million pixels–equivalent to 16 existing projectors today. E&S expects to have increased the capacity of its high-end Harmony IG in a flight simulator by 2005 to take full advantage of the laser projector to produce "eye-limited" resolution across large fields of view. (Ref 3.4)

1. Collimated Display Systems

a. Monitor Bases

The oldest type of visual display system used in flight simulators is the CRT monitor based collimator. The CRT collimator attempts to display the visual scene at a focal distance between 30 and 100 meters from the pilot. The collimator display unit

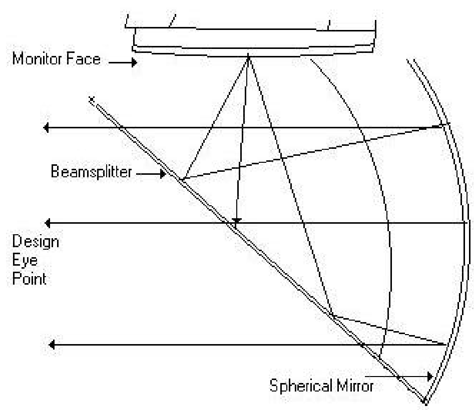

Figure 5: CRT Collimated Display (From: Ref 3.4)

includes a "high-resolution, 20- to 29-inch CRT monitor on top the simulator facing downward. The light rays from the face of the monitor reflect off an angled beamsplitter below it to a curved mirror behind the beamsplitter at the back of the unit. The light rays then reflect off the mirror as collimated light, and pass through the beamsplitter (a see-through mirror) to the pilot's eyes. The beamsplitter is made of optical-quality glass with an anti-reflective coating on the pilot's side and a semi-reflective coating on the mirror side. The beamsplitter reflects the CRT image to the curved mirror, but allows the pilot to look through it and see the distant-focus image in the curved mirror. The latter alters the angle of the light rays to the pilot, effectively making them parallel." (Ref 3.1) CRT collimators can be an individual unit or can be set up side by side to create a large field of view.

b. Panoramic Displays

Monitor based systems can adequately replicate night scenes but vertical black bars along the sides of the viewing area generally obscure its day scenes. Another problem is that in order to maintain a correctly focused and non-distorted display image the pilot must remain within a specified viewing area. Perspective errors are a significant problem when two crewmembers are seated side-by-side in a simulator due to the laterally separated eye points. Panoramic collimated displays or wide-angle, cross-cockpit collimated displays have been developed for aircraft that have side-by-side seating and need a wide field of view (~180–200 degrees horizontally) such as helicopters or transport aircraft. Panoramic displays use three to five projectors mounted

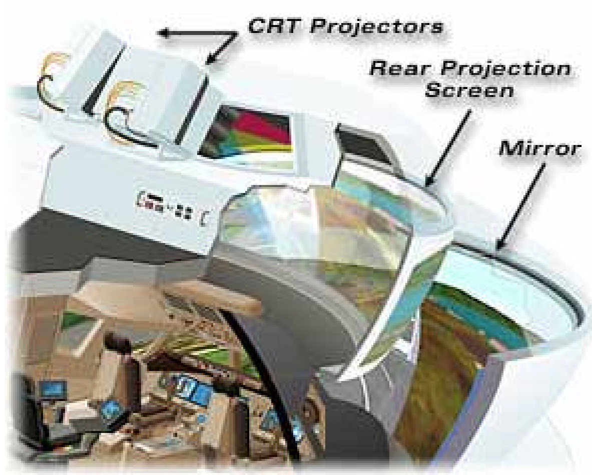

Figure 6: Panoramic Collimated Display (From: Ref 3.3)

atop the simulator cabin to project images on an intermediate screen above the crew compartment. The image on this back-projected screen is then reflected on a large concave mirror mounted in front of the simulator. The mirror's vertical curvature provides the distant focus implicit in collimated systems, and its horizontal curvature gives a continuous horizontal view without discontinuities thus enabling both crewmembers view the same visual scene without distortion. (Ref 3.2)

2. Dome and Mosaic Displays

Front- and rear-projection display systems are typically used for single-seat dome simulators or in mosaic multi-screen displays. Front-projection systems typically have several projectors mounted on the sides and top of the cockpit. They can project the visual imagery on a curved, wrap-around screen or dome with a horizontal field of view greater than 180 degrees. Rear-projection systems are popular because they remove the projectors from the cockpit area and eliminate shadows.

In rear-projected mosaic displays, flat panel screens are connected at different angles in a polyhedral structure, and a separate projector illuminates each panel using rear-projection from behind. Pilots typically focus their attention and pick up visual cues from the front and sides of the cockpit thus very-high-resolution imagery is concentrated in these areas. Separate target projectors can be mounted above the cockpit to provide a limited number of high-resolution air or ground targets on the display screens. The flat screens can provide up to a 360-degree horizontal field of view if desired, although this is not usually the case for non-dome simulators.

Figure 7: Rear-projected Mosaic Display (From Ref 3.5)

3. Helmet Mounted Displays

Figure 8: Helmet Mounted Displays (From Ref 3.6)

Helmet Mounted Displays (HMDs) enable bright, high-resolution, full-color computer-generated imagery to be projected over an unlimited field of regard. By monitoring the direction that the pilot is looking, visual imagery can be generated to cover the line-of-sight. HMDs can be combined with sensor simulations such as Forward Looking Infrared (FLIR) devices and night vision goggles (NVGs), to enhance tactical training exercises. CAE has even developed miniature CRTs driven directly by the image generator mounted within an actual NVG package that closely replicates the appearance of the aircraft units. (Ref 3.3)

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IV. HELICOPTER MATHEMATICAL MODELING (FLIGHTLAB)

A. OVERVIEW

Aircraft simulation has always been an important tool in the design and analysis of aerospace vehicles. Recent advances in simulation technology, coupled with reduced budgets have resulted in renewed emphasis on computer simulation for both test and evaluation, and training. The complexity of the dynamics and aerodynamics of rotorcraft vehicles are significantly more demanding than that of fixed wing aircraft. Consequently, the fidelity and computational power required for real time operation of rotorcraft simulation has, until recently, been accomplished using a very complex set of computer programs, a very powerful and expensive computer system, and a full motion based simulator.

Advanced Rotorcraft Technology, Inc. (ART) has pioneered standardization of flight dynamics modeling technology for helicopter engineering analysis through the development of FLIGHTLAB, a rapid prototyping tool for the development and analysis of high fidelity physics-based flight dynamics models. FLIGHTLAB also includes productivity tools for validation and configuration management in order to provide a total modeling and analysis environment. The Army and Navy are both utilizing FLIGHTLAB to develop and validate comprehensive helicopter simulation models of their helicopters for engineering design and analysis, and in support of test and evaluation. Real-time flight dynamics models derived from these FLIGHTLAB engineering models will be used in the Army's Aviation Combined Arms Tactical Trainer (AVCATT) simulators, a set of fixed base, reconfigureable collective training helicopter simulators. FLIGHTLAB allows selective fidelity modeling by using a library of modeling elements with varying levels of complexity. The sophistication of FLIGHTLAB models can therefore be customized to suit the application.

1. FLIGHTLAB Development System Overview

Advanced Rotorcraft Technologies, Inc has produced the FLIGHTLAB Development System, a Commercial-Off-The-Shelf (COTS) line of simulation productivity tools that have revolutionized the art of rotorcraft simulation.

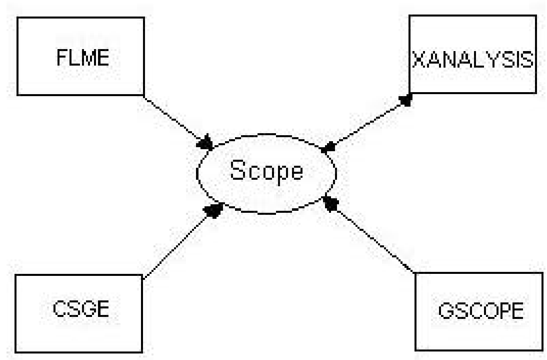


Figure 9: FLIGHTLAB Development System Components

Figure 9 depicts the interactions of the different components of the FLIGHTLAB Development System. The FLIGHTLAB Development System is based around a high-level interpretive language, called Scope, which combines FORTRAN and C computer languages with MATLAB syntax to facilitate the building and testing of a rotorcraft simulation model from a library of primitive modeling components. Users can select a component and connect and assign data to components via interactive a graphical user interface (GUI) or modeling script files which are developed using a text editor. (Ref 4.5)

The current version of FLIGHTLAB (2.11) uses a GUI tool, called FLIGHTLAB Model Editor (FLME), to generate models from subsystem modeling elements. A menu tree provides a visual representation of the aircraft subsystem, environment and other selective fidelity options at each subsystem in order to allow the user to customize the simulation for their application. The subsystem level modeling tool allows the user to specify the subsystem to be modeled, the modeling options and the data to be assigned. This information is then automatically converted to a modeling script file in Scope.

Early versions of FLIGHTLAB used a component level modeling tool called Graphical Scope (GSCOPE) to graphically construct the entire model by selecting components from a menu bar of icons, assigning data through dialog boxes and connecting components with a click of the mouse. (Ref 4.1)

Another component level modeling tool called the Control System Graphical Editor (CSGE) is used to model the aircraft's flight control and propulsion control systems as two dimensional block diagrams. The resulting schematic, similar to a SIMULINK model, is then automatically converted to a script file in the FLIGHTLAB language for use in the Model Editor or Xanalysis.

A third feature of the FLIGHTLAB Development System is Xanalysis. Xanalysis is an X-window based analysis interface used to support designing, testing and analysis of a rotorcraft model. Modification of the model's configuration and test conditions allows users to perform a set of basic analyses such as trim, linearization, model order reduction, and dynamic response analysis in the time and frequency domain. (Ref 4.4, Xanalysis) User specified analyses can be conducted on a single parameter or any combination of parameter values and the results of parameter sweeps can be displayed graphically. A set of predefined test scenarios support specialized rotorcraft analysis such as performance, stability and control, handling qualities and aerodynamic and structural loads. These predefined test scenarios and plot formats are based upon the standards used by the U.S Naval Test Pilot School at Patuxent River, MD. (Ref 4.5) The dynamic response of a simulation model can be directly compared against actual flight test data through the use of a data base management system. The simulation can be automatically configured to match the test vehicle's configuration and test conditions while using the time history of the test flight's control inputs to drive the simulation. A signal processing utility, which includes editing of bad test points, filtering high frequency noise and kinematic consistency testing using redundant sensor data, allows the user to condition test data prior to applying it for simulation validation.

B. SCOPE LANGUAGE

The FLIGHTLAB modeling suite uses Scope Language to support user-defined actions. Users can input individual instructions or write script files using Scope to manipulate the data generated by FLIGHTLAB. The Scope language is largely based upon the MATLAB syntax and functionality and consists of a set of commands and built-in functions that support general matrix manipulation, eigenvalue and Fourier analysis, as well as linear and non-linear systems analysis. The Scope Language Reference Manual describes the basic syntax and operations of the functions and commands supported by Scope.

C. FLIGHTLAB MODEL EDITOR (FLME)

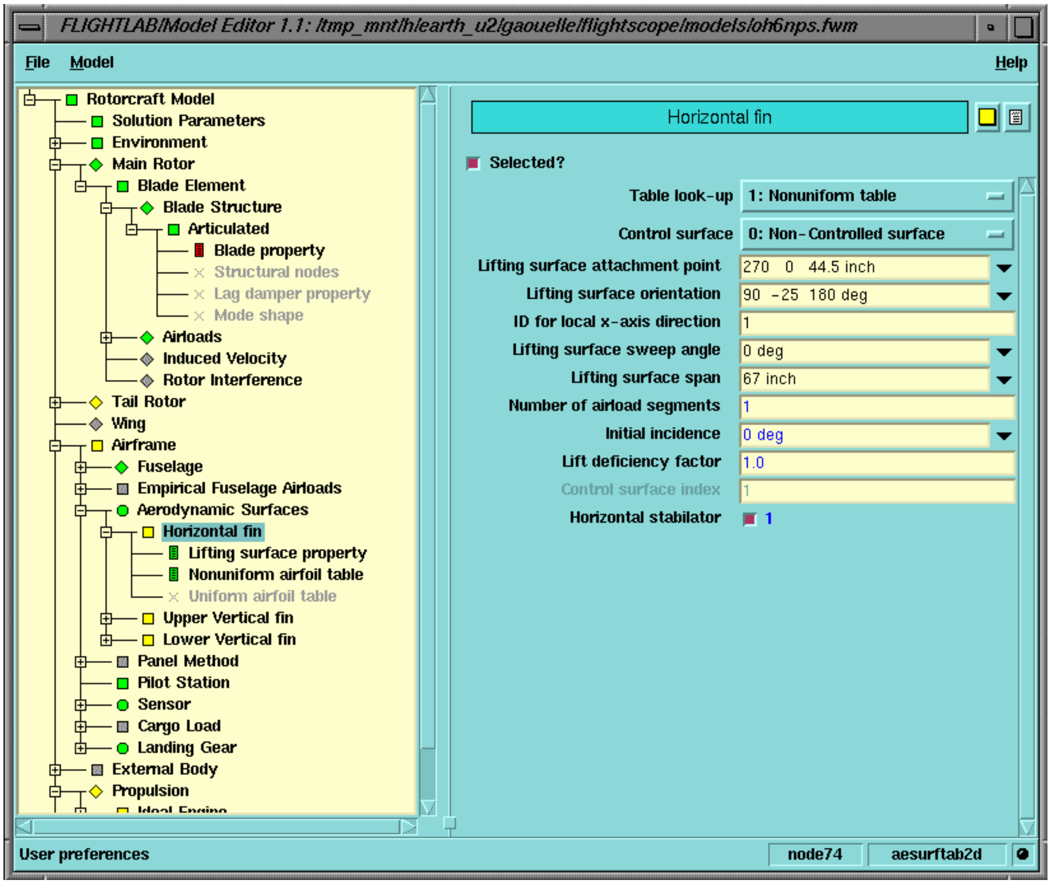


Figure 10: FLME Main Window

The FLIGHTLAB Model Editor is where the majority of the simulation data for the aircraft will be entered. The data is organized into hierarchical modules that correspond to a physical or logical subsystem of the aircraft model. When selected, FLME brings up one window with two panes as shown in Figure 10. The left hand pane displays the aircraft model as an expandable hierarchical tree structure and the right hand pane displays the data associated with the currently selected module.

1. Symbology

FLME uses several colors and symbols to represent the different features of the model. The colors of the hierarchical tree icons are used to denote the state of each node while the different icons represent the different options available to the user for that module.

The following colors are used in the model tree: Green indicates the user has marked the node as complete; Yellow means that the user has marked the node as incomplete; Gray indicates that the node has been disabled; Red indicates that there is an error associated with the node.

The most common icon is the square (?). The square in the model tree indicates the module only has associated user defined data parameters. A square in the data panel enables or disables the level of fidelity of the model. Selection of the square (mouse click in box) enables certain submodules and data parameters to be included in the model such as adding vortex interference. The circle (?) indicates that a module is repeatable. A repeatable module may have more than one occurrence such as an aerodynamic surface like a horizontal or vertical stabilizer. The diamond (?) indicates that the module contains a choice of several different modeling options. An example of such a module is the Blade Structure module; the user has the option of using an articulated, hingeless, teetering, or gimbaled rotor head. Upon selection, the model tree will dynamically change to reflect the required data parameters and submodules associated with the option chosen. The table symbol () indicates that the data for the node appears in an external data file. Finally, the paperclip symbol () indicates that there is associated external data file (attachment) that is not used by FLME but may be of interest to others. (Ref 4.4, Model Editor)

2. Top Level Modules

FLME can be used to create an entire fixed wing or rotary wing aircraft model, an isolated rotor model or an isolated flight control model. A typical rotorcraft model includes submodules as described below. (Ref 4.4, Model Editor)

a. Solution Parameters

This template specifies the simulation solution parameters for Newton-Raphson solution and simulation integration time step length.

b. Environment

This template models the atmospheric properties and wind conditions. It includes options to use various atmospheric tables such as: standard day, cold day, polar day, tropical day, and hot day as well as a table of altitudes for various temperature gradients.

c. Rotor1 (Main Rotor)

This template defines the rotor model used to model the main rotor (single main rotor), front rotor (tandem rotor), left rotor (tilt rotor), or upper rotor (coaxial rotor). The model uses either a blade element or finite element parameters to define an articulated, hingeless, teetering, or gimbaled rotor head.

d. Rotor2 (Tail Rotor)

This template defines the rotor model used to model the tail rotor (single main rotor), aft rotor (tandem rotor), right rotor (tilt rotor), or lower rotor (coaxial rotor). The rotor can be modeled as a Bailey Rotor, Blade Element, Ducted Fan or Rotor map with interference. The Blade Element model can be either an articulated, hingeless, teetering, or gimbaled rotor head.

e. Wing (Composite Rotorcraft)

This module is intended to model a rigid main wing with associated wake and interference fidelity options.

f. Airframe

This template includes a fuselage (rigid or elastic), aerodynamic lifting surfaces (stabilizers), sensors (motion, accelerometers and slip ball), landing gear, empirical fuselage airloads and pilot station interface.

g. External Body (Swing Loads)

This template describes the features of an external load and associated airloads.

h. Propulsion

This template provides options for an ideal engine (constant rotational speed and unlimited power output), simple engine (include engine governor dynamics) or a high fidelity turboshaft engine.

i. Flight Controls

This template provides only the basic features of the aircraft flight controls. Higher fidelity models are created in the Control Systems Graphical Editor (CSGE) and imported into the model.

3. Tables

Data tables can be created using the .TAB file format, which is easy to read and edit or .SAV file format, which is convenient for large data sets. Data tables can be listed as either a table, indexed table or in a matrix form.

D. CONTROL SYSTEM GRAPHICAL EDITOR (CSGE)

The CSGE is a GUI editor that enables a user to design and build a two-dimensional block diagram schematic of a control system. When the control system is built, a FLIGHTLAB executable script is generated for inclusion in FLME.

1. CSGE Usage

The CSGE is similar in function to SIMULINK in MATLAB. The CSGE consists of a design canvas and an element toolbox, which contains seven different types of elements: linear elements, logical elements, discrete elements, non-linear elements, trigonometric elements, input/output elements, and a superblock element. See Figure 11.

In order to create an element to use, first the element is selected in the toolbox and then the desired location on the canvas is selected, which creates the element. Clicking and dragging from the connection handle of the source element to the desired connecting element connect elements. Double clicking on an element displays a dialog block that enables the user to vary the properties associated with the element. Double clicking on the superblock enables the user to move to a lower level design, which displays the elements that make up the superblock. Each element can be resized, rotated and renamed to suit the users desires.

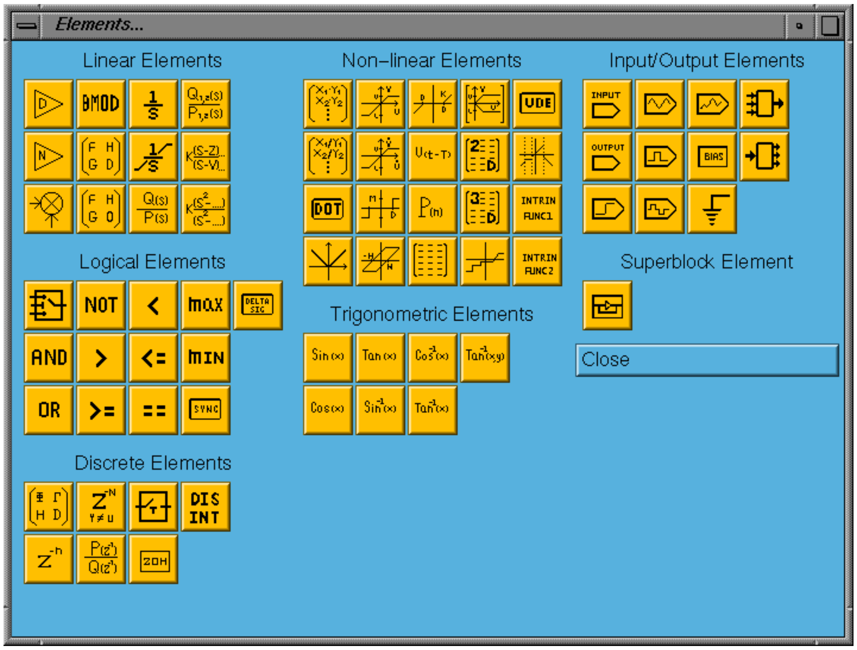


Figure 11: Control System Graphical Editor (CSGE) Toolbox

2. Designating Inputs and Outputs

a. Inputs

CSGE inputs from the helicopter model are designated in the input element block. Double clicking on the input element block brings up the element properties dialog window. The input value is either a constant or the location in the FLIGHTLAB model where the value associated with the input is kept. Data for the flight control system are kept in the directory world_model_control_data where the underscore designates subdirectories within the FLIGHTLAB model and is how the Scope language writes its variables.

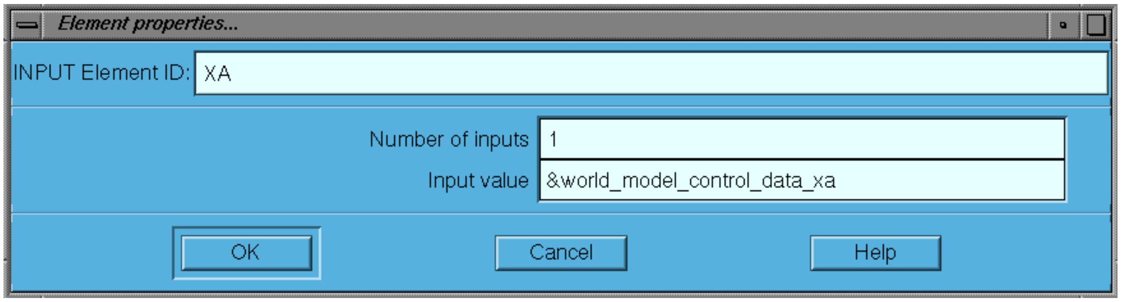


Figure 12: Element Properties Window

Outputs from one CSGE model can be used as inputs to another CSGE models. These values can be accessed via the input interface dialog window. This window is accessed by selecting the FLIGHTLAB pull down menu on the CSGE main window (canvas) and selecting INPUTS FOR MODEL INTERFACE. The following dialog window will be displayed:

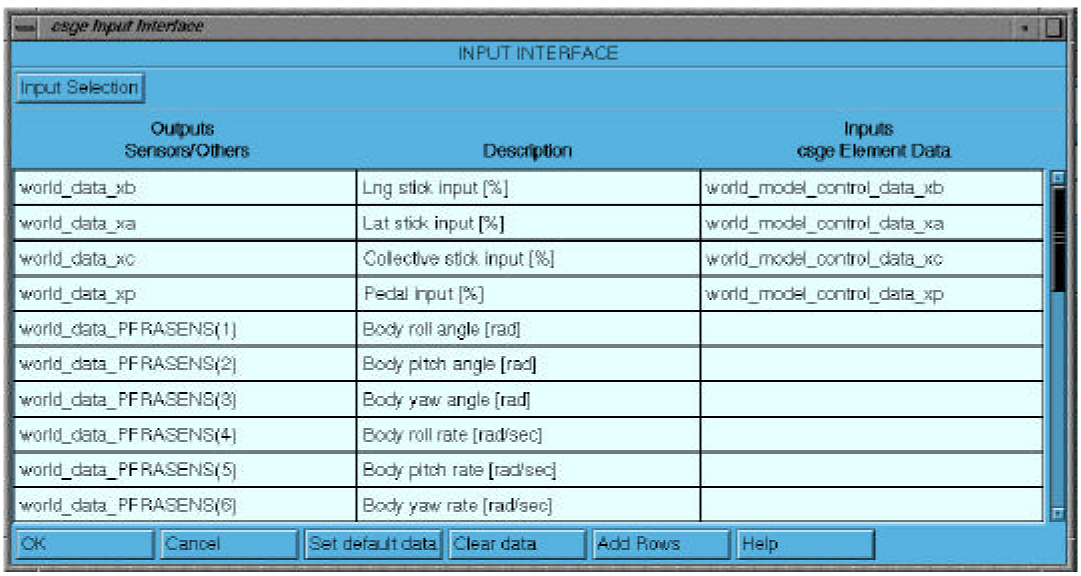


Figure 13: Input Interface Window

Selection of the SET DEFAULT DATA push button will automatically display outputs and descriptions of a typical flight control system. The OUTPUTS SENSORS/OTHER column designates a convenient location where other CSGE modules save their data. The DESCRIPTION column describes the variable data in an easy to read format. The INPUTS CSGE ELEMENT DATA column designates the location where your CSGE model accesses the input data. Providing an input variable name thus correlates the output of one CSGE model with the input of another.

b. Outputs

Outputs are designated in the output interface dialog window. This window is accessed by selecting the FLIGHTLAB pull down menu on the CSGE main window (canvas) and selecting OUTPUTS FOR MODEL INTERFACE. The following dialog window will be displayed:

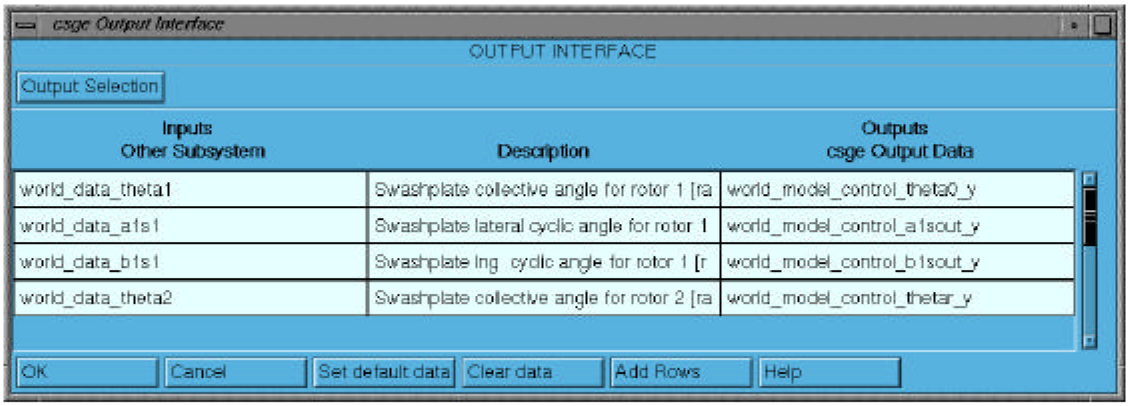


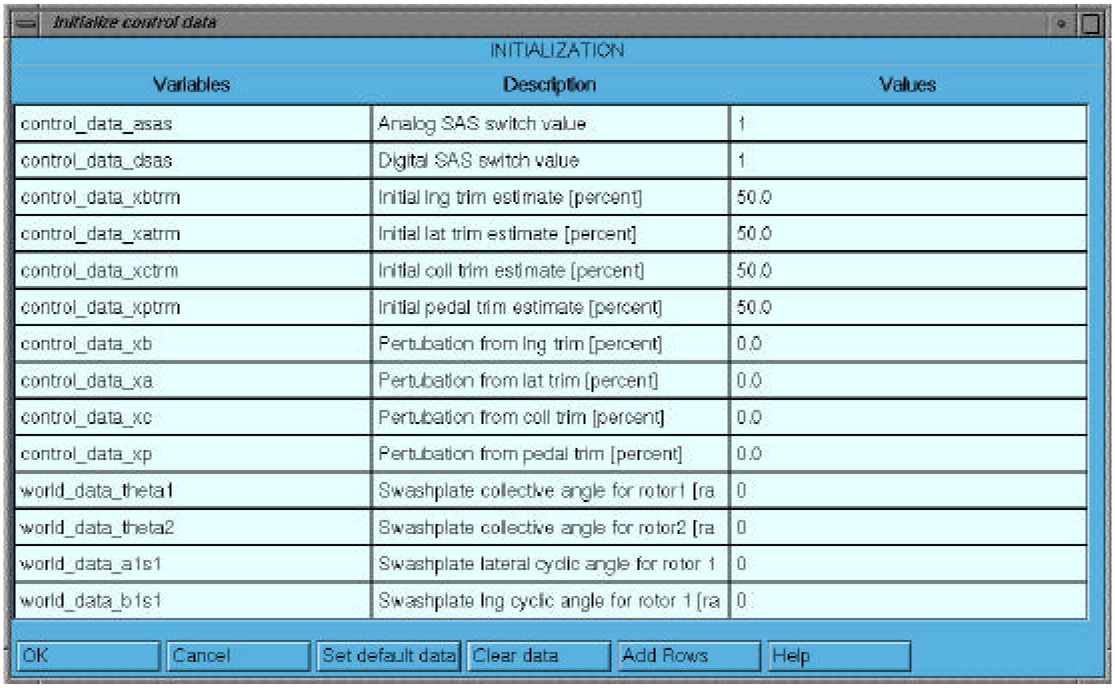
Figure 14: Output Interface Window

Selection of the SET DEFAULT DATA push button will automatically display inputs and descriptions of a typical flight control system. The INPUTS OTHER SUBSYSTEM column designates the variable location where other CSGE modules can access the data. Since the data may be used in another flight control CSGE module (e.g. Engine Control Unit) the data is saved external to the control directory (i.e. world_data) in a convenient location for external use. The DESCRIPTION column describes the variable data in an easy to read format. The OUTPUTS CSGE OUTPUT DATA column designates the location where the data is saved in your CSGE model. The subscript "*variablename*_y" tells Xanalysis that the data is the final value associated with the current iteration.

c. Initialization

The .prolog file contains the variable initialization data. This data is produced via the Initialization dialog window. Selecting the FLIGHTLAB pull down menu on the CSGE main window and selecting INITIALIZE CONTROL DATA access this window. The following dialog window will be displayed:

Selection of the SET DEFAULT DATA push button will automatically display variables of a typical flight control system. The VARIABLES column designates the location where the initial value of the variable is kept. The DESCRIPTION column describes the variable data in an easy to read format. The VALUES column designates the value to be set upon initialization.



Variables	Description	Values
control_data_asas	Analog SAS switch value	1
control_data_dsas	Digital SAS switch value	1
control_data_xbtrm	Initial lng trim estimate [percent]	50.0
control_data_xatrm	Initial lat trim estimate [percent]	50.0
control_data_xctrm	Initial coll trim estimate [percent]	50.0
control_data_xptrm	Initial pedal trim estimate [percent]	50.0
control_data_xb	Pertubation from lng trim [percent]	0.0
control_data_xa	Pertubation from lat trim [percent]	0.0
control_data_xc	Pertubation from coll trim [percent]	0.0
control_data_xp	Pertubation from pedal trim [percent]	0.0
world_data_theta1	Swashplate collective angle for rotor1 [ra	0
world_data_theta2	Swashplate collective angle for rotor2 [ra	0
world_data_a1s1	Swashplate lateral cyclic angle for rotor 1	0
world_data_b1s1	Swashplate lng cyclic angle for rotor 1 [ra	0

Figure 15: Initialization Window

d. External Inputs/Outputs

The external input and output list for results processing dialog windows associate external variables used for processing in Xanalysis with variables used in the CSGE model. Selecting the FLIGHTLAB pull down menu on the CSGE main window and selecting INPUTS FOR EXTERNAL DEVICE accesses the external input dialog window. The following dialog window will be displayed:

Selection of the SET DEFAULT DATA push button will automatically display typical flight control system correlations. The EXTERNAL INPUTS column designates the CPG location where external functions (i.e. Xanalysis dialog boxes) can access the initialization data. The DESCRIPTION column describes the variable data in an easy to read format and is what Xanalysis displays it its dialog boxes. The CSGE

INPUT DATA column designates the location where your CSGE model access its information and is generally the same location as the initialization data.

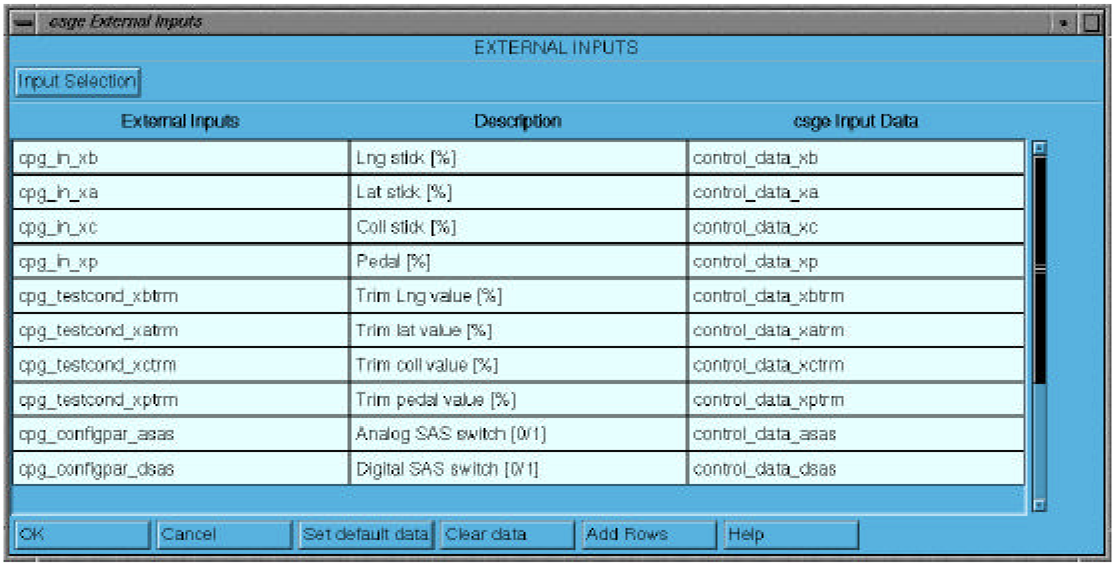


Figure 16: External Inputs Window

Selecting the FLIGHTLAB pull down menu on the CSGE main window and selecting OUTPUTS FOR RESULTS PROCESSING access the output list for results processing dialog window. The following dialog window will be displayed:

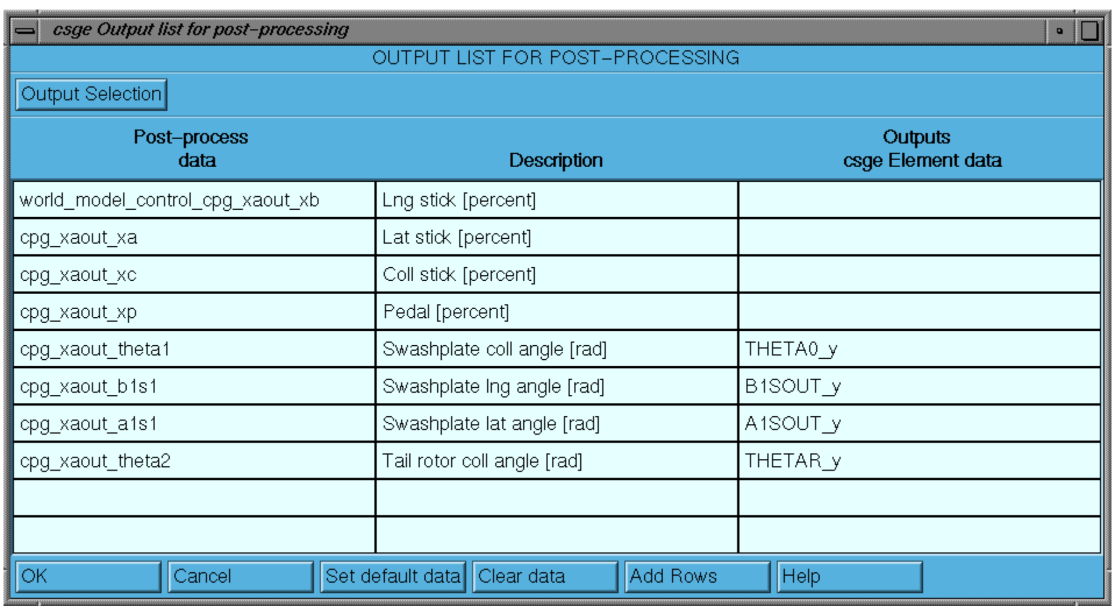


Figure 17: Output List for Post-Processing Window

Selection of the SET DEFAULT DATA push button will automatically display typical flight control system correlations. The POST-PROCESSING DATA column designates the correct CPG group location of the outputs of the control system so that the data can be accessed via the menu windows in Xanalysis. The DESCRIPTION column describes the variable data in an easy to read format. The OUTPUTS CSGE ELEMENT DATA column designates the location where the data is saved in your CSGE model. The subscript "*variablename*_y" tells Xanalysis that it is an output from a CSGE model.

3. Exporting to FLME

Selecting export from the FLIGHTLAB tab of the CSGE menu bar generates the .exc, .prolog, .epilog, and .configure files. The .prolog file contains the initial conditions of the controls and is the first file used in FLME. The .exc file contains the graphical representation of the control system in Scope script format. The .epilog file sets up the connections between the different model groups. The .configure file defines the data dictionary for the associated model group thus creating the necessary group structure and is the last file used in FLME.

E. XANALYSIS

Xanalysis is a GUI designed for the analysis of the dynamic system models created in FLIGHTLAB. It provides a convenient tool for rapid, detailed and intensive dynamic system testing, performance, control, and stability analysis. Users can use utilities such as Trim, Static Equilibrium, Steady State, Linearization, Eigenanalysis, Model Order Reduction, Time and Frequency Responses and Parameter Sweep or perform specific simulations/analysis scenarios such as Performance and Stability, Loads, Handling Qualities, Control Design, Signal Processing, Code Generation, Pilot-in-the-loop Simulation, etc.

Xanalysis also provides a workspace to create scenarios and conduct analysis using the Scope Language and display the results of any of the utilities listed above.

F. PILOTSTATION

PilotStation, a turnkey simulation executive, processes the high fidelity rotorcraft model, generates the cockpit gauges and out the window displays and interfaces the model through an operator/instructor console. PilotStation is a real-time, distributed-architecture simulation executive that couples the image generation and pilot control inputs with the FLIGHTLAB flight dynamics model. PilotStation provides a desktop interface with the FLIGHTLAB model. It can be run on UNIX or LINUX platforms and is expandable from a single computer desktop simulator to a networked multi-computer full motion based simulator with control loaders and a three window visual display. PilotStation provides plug and play utilization for a range of hardware devices including joysticks for desktop simulators, electrical control loaders for Operational Flight Trainers and motion platform drives. Computer software handles the computations of the reaction of aerodynamic and gravitational forces between the model components. Unlike a linear model, which is valid only in a small linear region, PilotStation produces a non-linear analysis, which is valid over the entire flight envelope. This program allows a user to develop a high fidelity, interchangeable, helicopter design, which includes the rotor degrees-of-freedom as well as the six-degrees-of-freedom of the body. (Ref 4.5)

V. HELIFLIGHT II

A. OVERVIEW

HeliFight II is ART's initial production, low cost, full motion helicopter flight simulator. HeliFight II provides realistic pilot cues in a fully immersed environment designed for effective training on maneuvers ranging from hover to autorotation. HeliFlight II uses a high fidelity flight dynamics model developed under FLIGHTLAB to provide accurate simulation of rotor dynamics and aerodynamics. Physical motion cues are provided by a six-degree of freedom, electromagnetic ram motion platform. Low levels of transport delay effectively correlate motion and visual cues. Electrical actuators in all four-control axes provide realistic stiffness and damping simulation of the flight controls. Characteristics may be varied in software to represent control loads for a wide range of helicopters.

B. CONFIGURATION

1. Visual System

A high-quality visual system is required to give pilots the depth perception essential for precision maneuvers such as hovering and autorotation flare. Image generation is accomplished through three Evans and Sutherland (E&S) Simfusion 4000 computers. These are high-level dual processor PCs equipped with E&S graphics acceleration hardware, which produces a steady 60 Hz update rate with full screen anti-aliasing. Anti-aliasing is required to clearly render straight lines in terrain features such as power lines and fences. It is also needed to eliminate distracting visual artifacts such as "object popping", "edge crawling" and Moiré patterns in texture maps. Complex visual databases are rendered through XIG, a library of OpenGL utilities. Heliflight II's visual system uses three 3Dperceptron projectors that provide high resolution and high brightness image to a 180-degree horizontal by 50-degree vertical field of view curved screen display. Distortion correction for the curved screen displays and edge blending is accomplished via software control of the projectors. (Ref 5.1)

2. Operator/Instructor Console

Control of the simulation session is performed with the Operator/Instructor Console. It allows the Operator/Instructor to customize a training scenario to include specifying a pre-stored scenario, specific failure modes, vehicle configuration, environmental changes, and specification of data to be recorded.

The console unit consists of two computers, each with dual Pentium 4 1.4 GHz processors, to process the FLIGHTLAB flight dynamic model in real time and run the console software. PilotStation, ART's proprietary distributed simulation software, is run on the second processor of each computer to tie together the computers used to drive the system. The console houses a software programmable three axis side-arm controller, switches, and levers. Six video displays provide the interactive interface and reproduces the three out-the-widow scenes, and instrument display and a Stealth view of any vehicle in the mission scenario. (Ref 5.1)

3. Aircraft Modules

A six-degree of freedom Control Loader Platform is the mounting base for the interchangeable cockpits. It consists of separate Pilot and Copilot platforms that can be linked together to represent any cockpit configuration. Interchangeable sticks, grips and instrument panels may be mounted on these platforms. The platforms, in turn, are surrounded with an aircraft specific cockpit enclosure that provides realistic visual restriction and cockpit environment. Computer generated images of the analog gauges are displayed on a flat panel video display and visible through cutouts in the instrument overlay. Four sets of electrical control loaders are used to back drive the longitudinal cyclic, lateral cyclic, collective and pedal controls and are software configurable for emulating the loading characteristics of different helicopter configurations. The control attachment points are placed at an average location for a range of helicopters and the control sticks are modified for each aircraft type. A fifteen-foot diameter sphere provides the outside enclosure upon which the out-the-cockpit widow scene is projected. Two additional seats mounted in the sphere behind the cockpit allow for an on-board Operator/Instructor as well as an observer. (Ref 5.1)

4. System Options

The Heliflight II can be configured as three different systems; an Open Platform, Fixed Base, and Motion Base. The Open Platform system is a low cost option that provides the essential elements of the simulator in a standard office environment. The components are highly portable and consist of the Control Loader Platform, Operator/Instructor Console, and Visual System with a free standing cylindrical screen and a truss for mounting the projectors. The Fixed Base system consist of the Control Loader Platform, Operator/Instructor Console, and Visual System mounted in a spherical capsule. The Motion Based system consists of the same equipment of the Fixed Based system only mounted on six degree of freedom electrical actuators. An intercom provides cockpit communications and safety interlocks preclude operation of the motion platform if it is not properly secured. The Motion Based system satisfies all FAA standards for Level C simulators. (Ref 5.1) See Appendix A for an explanation of the FAA standards.

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VI. OH-6A MODEL

Figure 18: OH-6A Cayuse (From Ref 6.24)

A. COORDINATE SYSTEM

1. Fuselage Coordinates

The location of all components of the OH-6A are described in terms of a three-axis coordinate system. Each axis, Fuselage, Waterline and Buttline, consists of one-inch segments called stations. The aircraft Fuselage stations run fore to aft with fuselage station zero 28 inches in front of the nose of the aircraft. The aircraft Waterline stations run vertically up the aircraft. Waterline station zero is approximately 12 inches above the deck and is aligned with the lowest portion of the fuselage. The aircraft Buttline stations run horizontally left and right of the aircraft with station zero being the center line of the aircraft and positive values going to the left (port). It is noted that the body coordinate system is X (forward), Y (right), and Z (down), in accordance with the right hand rule. Thus the Fuselage, Buttline, and Waterline are positive in the opposite directions to X, Y, and Z respectively.

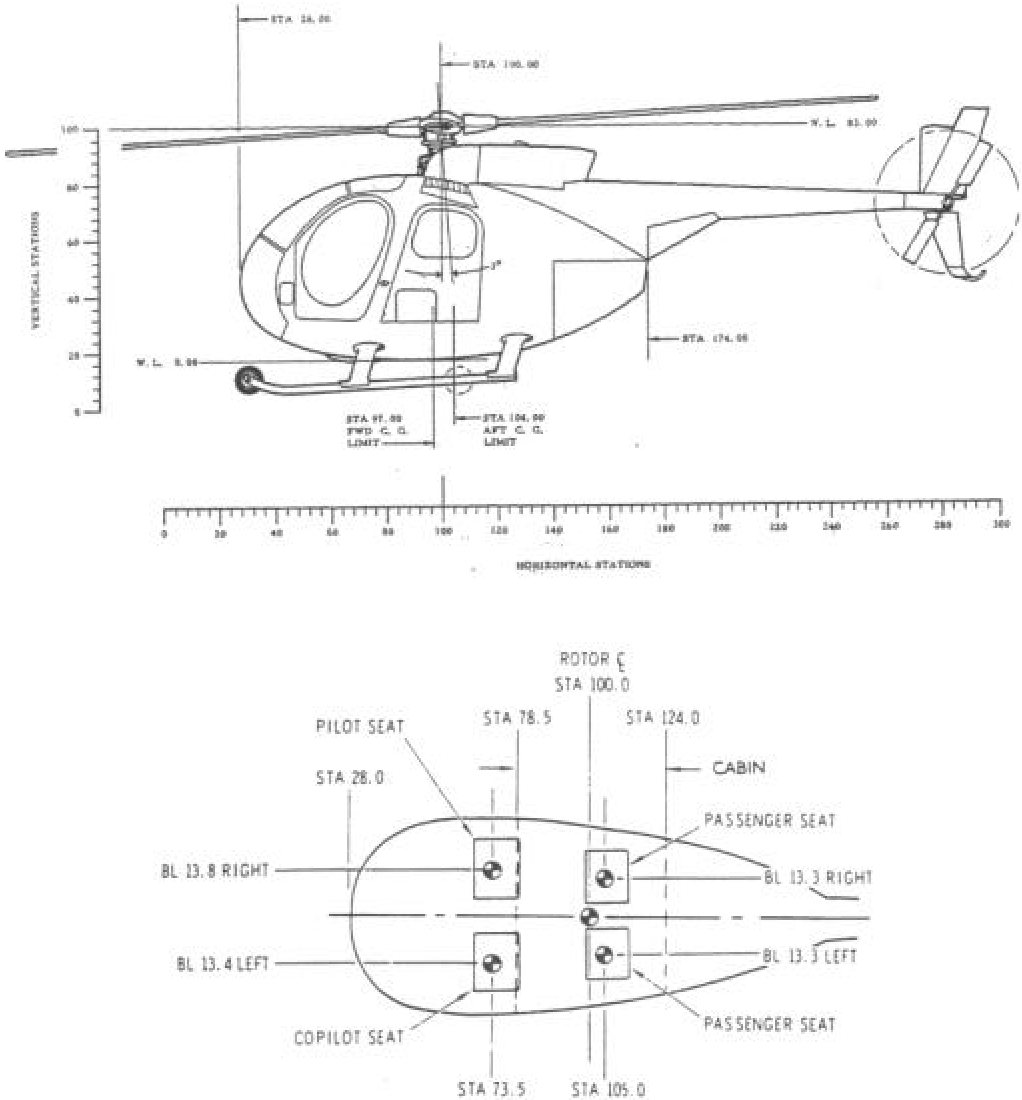


Figure 19: OH-6A Aircraft Measurement Stations (From: Ref 6.2)

2. Main Rotor Head Coordinates

The main rotor head stations are measured from the center of the rotor hub outward to the ends of the rotor blades in one-inch segments.

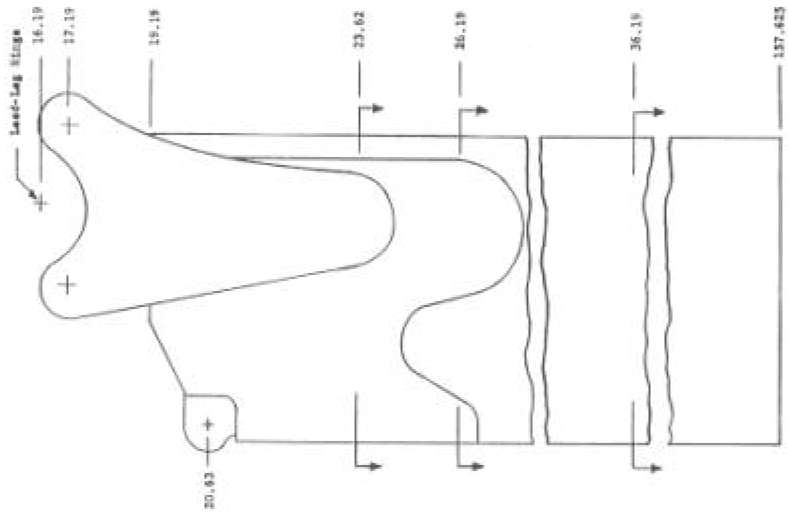


Figure 20: OH-6A Main Rotor Blade (From: Ref 6.1)

The blade chord is measured from the leading edge to the trailing edge of blade. The feathering axis and center of gravity are approximately the ¼ chord point, which is .375 inches in front of the axis of rotation. The elastic axis is approximately .91 inches in front of the ¼ chord point.

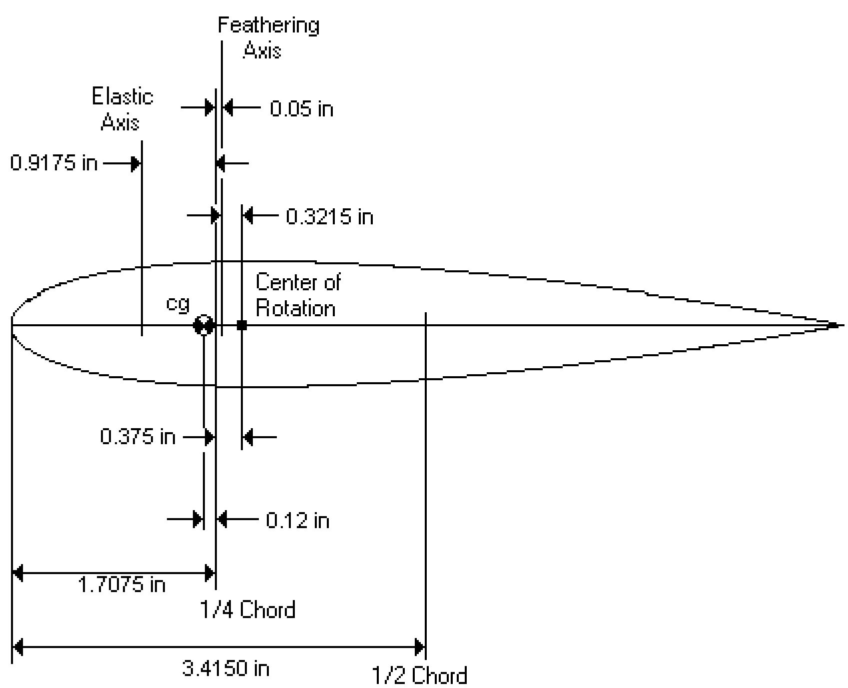


Figure 21: Main Rotor Blade Airfoil Section

3. Euler Angles

FLIGHTLAB uses Euler angles to describe the orientation of the different components of the aircraft with respect to the body frame. FLIGHTLAB inputs the data using the convention of PSI, THETA, and PHI. This is consistent with the standard 3-2-1 axis of rotation convention.

4. NACA 0015 Airfoil

The main rotor, tail rotor, and horizontal and vertical stabilizers are all modeled as NACA 0015 airfoil segments. While this is not the correct airfoil for the tail rotor or the vertical stabilizers it was determined that modeling theses surfaces as a NACA 0015 airfoil will not have a noticeable affect on the overall dynamics of the aircraft. The data used to model the airfoil was obtained from wind tunnel tests conducted at Sandia National Laboratories in 1981. (Ref 6.3) Appendix B shows a graphical representation of the data published.

B. ROTORBLADES

1. Main Rotor Head

The OH-6A main rotor is a fully articulated, four-bladed system with a radius of 157.63 inches. The blade is a NACA 0015 airfoil section of a constant chord length of 6.83 inches incorporating a trailing edge extension yielding an overall chord of 7.21 inches. It has a constant leading edge with a uniform twist of –9 degrees measured from the center of the rotor hub to the end of the rotor blade. A 2.995-pound vibration absorber assembly is attached at blade station 23.4 consisting of two pendulums tuned to absorb 3/rev and 5/ rev vibrations. These vibration absorbers are not installed on the MD 369 (the commercial version of the OH-6A). A similar pendulum absorber system was proposed for use on the AH-64 Apache but was eventually ruled out following subsequent engineering analysis.

The main rotor hub assembly consists of a central hub attached to the main rotor drive shaft and four identical pitch housing assemblies located 90 degrees apart and slightly offset with cross connected retention straps (strap pack). The main rotor head shaft rotates at a nominal 483 rpm and is tilted 3 degrees forward. Centrifugal force is transmitted from the blade through the lead-lag hinge to the outboard end of the strap

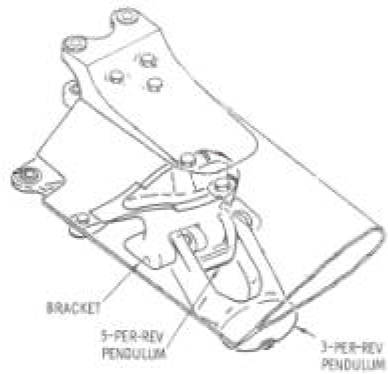


Figure 22: Pendulum Absorbers (From: Ref 6.5)

pack and is reacted by the centrifugal force of the opposite blade. Flapping and pitching motions are accommodated by structural deformation of the strap packs due to their inherent flexibility. The flapping and feathering hinge located at blade station 5.5 serves primarily as an alignment point and consequently this hinge offset produces a phase angle of approximately 86 degrees. A friction type damper mounted on each pitch housing is connected to the inboard trailing edge of the associated rotor blade to limit blade movement about the lead-lag axis and to prevent potential ground and air resonance instability. The lead-lag hinge located at blade station 16.188 allows for lead-lag blade motion to the Coriolis inplane moment generated by blade flapping.

A notable feature of the OH-6A rotor head is the use of a "static" mast concept. Unlike a more conventional "dynamic" mast that suspends the helicopter fuselage beneath the rotor, a "static" mast allows the rotor to rest directly on a bearing that is rigidly mounted to the airframe. To accomplish this design the OH-6A rotor driveshaft extends through the hollow center of the mast and is connected to the rotor on one end and the main transmission on the other. This ensures that the main rotor driveshaft is only subjected to torque from the engine and all aerodynamic loads are thus passed directly to the airframe structure. This eliminates large 1 /rev cyclic loads in the rotor support system thus improving its fatigue characteristics. The "static" mast concept subsequently reduces the rotor and driveshaft weight and enhances drive system reliability. (Ref 6.24)

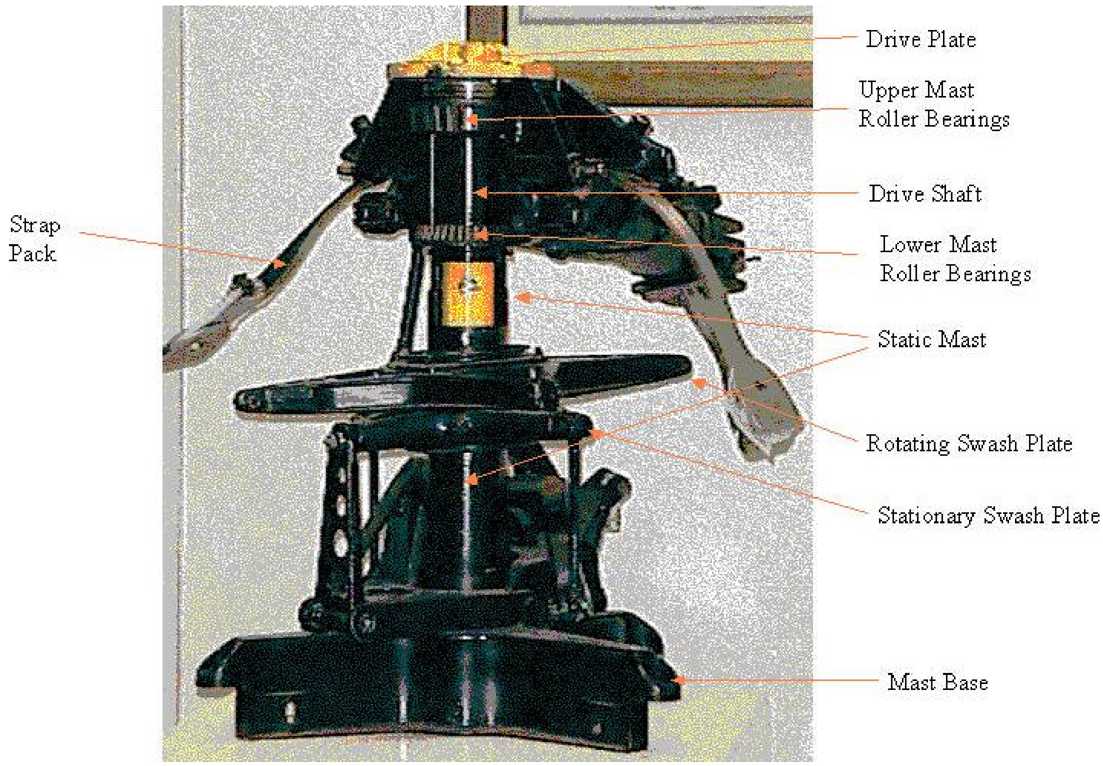


Figure 23: Main Rotor "Static Mast"

2. Tail Rotor

The OH-6A tail rotor is a two-bladed, teetering delta type system with a 4.25-foot diameter. The blade is a NACA 0014 modified airfoil section with constant chord length of 4.81-inches with a –7 degree twist measured from the center of the tail rotor hub to the end of the blade. The tail rotor incorporates a delta-3 hinge angle of 43 degrees and has a built-in precone angle towards the tailboom to relieve flapwise bending stresses when thrust loads are applied.

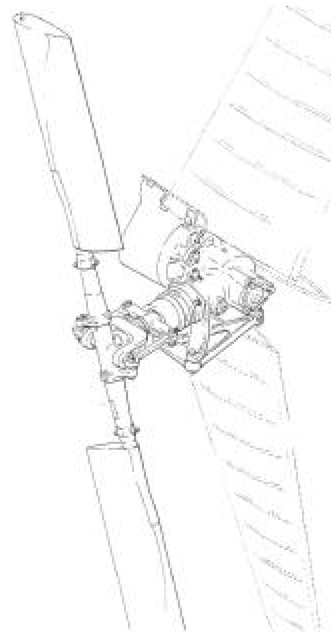


Figure 24: Tail Rotor (From Ref 6.5)

3. Blade Property Table

The Blade Property Table for the main rotor blade was adapted from data of the 369D/E 5-bladed rotor system. The data used is the same data Boeing used in their rotor analysis program called DART (Dynamic Analysis Research Tool). DART is a general finite element program developed in the early 1970's to automate the aeroelastic analysis of a rotor blade. DART utilizes four basic element types (mass, damper, elastic, and equations of constraint) to perform four basic types of analysis: Real eigenvalue analysis (vibration modes); Complex eigenvalue analysis of fully coupled linear equations of motion (flutter); Frequency response analysis (harmonic response); Transient response analysis to time-varying force excitations, including nonlinear effects. (Ref 6.7)

The blade differences are minimal in nature and are:

1. The blade flap hinge and lag hinge of the 369D/E are moved radially outboard by 0.5 inches.

2. The 369D/E uses an elastomeric lead-lag damper while the 369C uses a friction type damper.

3. The 369C has a tuned 3/rev and 5/rev pendulum absorber attached to the blade at station 23.4.

Since the blades are so similar, the table was constructed using the data for the ends of the blades while removing 1 inch of data from the center of the blade. The data at the center of the blade is relatively constant and removing the data yields no significant degradations to the model. Appendix B contains the rotor blade data used in DART and was provided by Mr. Lou Silverthorn of Boeing.

Explanations of some of the conversion factors are as follows: Cg offset is measured from the elastic axis. Ic is a planar (vertical plane) second mass moment of inertia that is related to the incremental mass times chordwise distance squared integrated over the cross-section. Ib is a planar (horizontal plane) second mass moment of inertia that is related to the incremental mass times beamwise distance squared integrated over the cross-section. The summation of Ib and Ic gives a second mass moment of inertia about an axis defined by the intersection of the two planes (cross-sectional c.g.) FLIGHTLAB variables Iy and Iz are flatwise and chordwise mass moments of inertia lumped at each end of the finite elements. While for the torsional degree of freedom, the moment of inertia of each section is the dominant inertia element in the mass matrix; this is not true for the blade bending degrees of freedom. For the blade bending degree of freedom, the main inertia terms are the lumped masses and the geometric distances between the lumped masses. The additional rotational (flapwise or chordwise) inertias are generally small and are frequently neglected if there are a large number of finite elements used in the rotor beam model. Since DART does not provide the values for the flapwise or chordwise inertias, they were set to zero.

C. FUSELAGE

1. Fuselage

The fuselage skin is composed mainly of sheet metal paneling; with the frame supports constructed out of aluminum alloy and the canopy windows of clear or smoke-gray-tinted cast acrylic depending on location. The lower section center beam, the station 78.5-canted frame and the station 124.0-canted frame and lower section frame are the primary structural members of the helicopter.

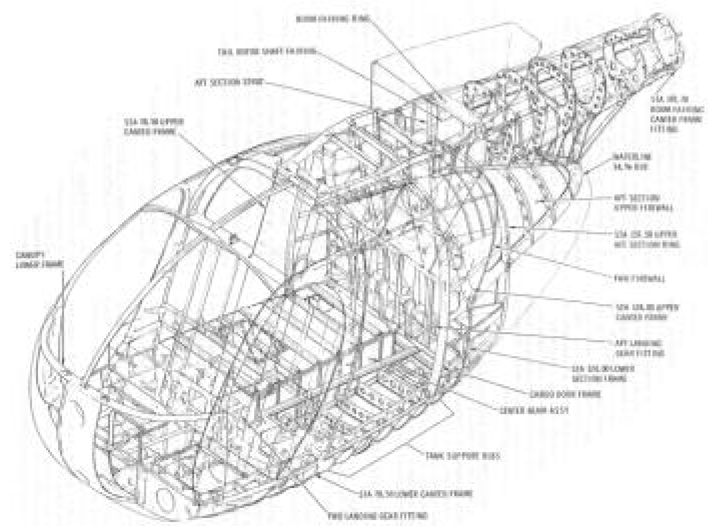


Figure 25: Fuselage (From Ref 6.5)

A pitot static tube is located low in the center of the forward section approximately level at the water line. The battery and electrical compartment are located below the left front seat and the fuel tanks are located below the rear seats.

The tailboom assembly is a semi-monocoque structure of aluminum skin over forged aluminum frames. It houses the tail rotor drive shaft and tail rotor control rod while supporting the horizontal and vertical tail surfaces.

a. NASTRAN/PATRAN Model

In 1996 NPS obtained a NASTRAN fuselage model of a MD-500 from Dr. Mostafa Toosi of the McDonnell Douglas Helicopter Company. The MD-500 fuselage is very similar to the OH-6A and students working for Dr Wood were able to modify the model to accurately reflect the OH-6A fuselage by replacing the “T-tail” with the canted horizontal stabilizer.

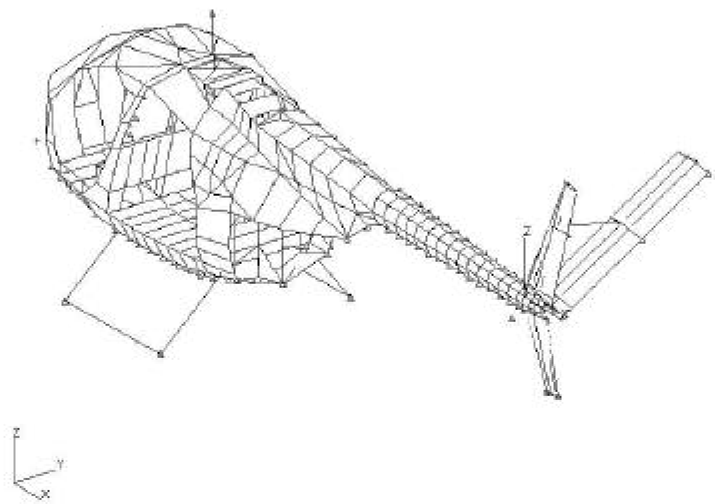


Figure 26: NPS NASTRAN Model

Mode	MDHC Test (Hz)	NPS Test (Hz)	NASTRAN Model (Hz)
First Lateral	8.40	9.32	8.35
First Vertical	9.30	9.97	9.9918
First Torsional	14.40	15.01	1.8927
Aft Vertical	15.50	15.61	-
Second Vertical	20.70	21.83	19.839
Second Lateral	26.40	27.48	13.571
Second Torsional	-	-	15.404

Table 2: OH-6A Mode Frequencies

Table 2 is a comparison of the MDHC "shake" test results, the NPS "shake" test results and the NASTRAN model predictions. The NASTRAN model, like the MDHC "shake" test aircraft is measured at close to maximum gross weight (2500 pounds) while the NPS "shake" test aircraft was measured close to the minimum gross weight (1500 pounds). Measuring vibrational frequencies at a higher gross weight will tend to lower the resonant frequencies as can be see in Table 2. The NASTRAN model predicted 33 different modes, six of which are the rigid body (zero frequency) modes. Most modes predicted were a combination of lateral or vertical with torsional coupling.

The frequencies in Table 2 list modes that were primarily lateral, vertical or torsional modes. The second torsional mode of the NASTRAN model correlates with the first torsional mode of the "shake tests". Since the first torsional mode of the NASTRAN model is so low (1.8927 Hz) it may not have been picked up by accelerometers due to close coupling with the "bungee" chord-pulley suspension system tuned to 1Hz. The aft vertical mode was not seen in the NASTRAN model.

Since the NPS and the MDHC results are from actual "shake tests" of full scale OH-6As it is obvious that there are mass element positioning errors in the NASTRAN model. First, the horizontal stabilizer to the NASTRAN model may not be modeled accurately. The OH-6A model is a modified MD-500 model thus the weight distribution or structural stiffness of the stabilizer may be slightly off which would add or change the frequencies of several of the modes investigated. Next, several modes in the NASTRAN model tend to be driven by the landing skids; suspect that the landing skids are incorrectly modeled because these modes are not seen in either "shake" test.

b. Fuselage Aerodynamics Model

The fuselage aerodynamic data was derived from wind tunnel tests conducted at NASA Ames Research Center's 40-ft by 80ft full scale wind tunnel in 1969 (Ref 6.1) and during the U.S. Army's production competition for a Light Observation Helicopter (LOH) (Ref 6.15) in 1967. Mr. Scott Sather at Boeing provided the LOH data. See Appendix C for a MATLAB graphical presentation of the fuselage aerodynamic data (with the empennage off) collected during the LOH wind tunnel tests and theoretical analysis based on the UH-60A to fill in the gaps where wind tunnel values do not exist. Dr. Hong Xin of ART assisted in generating this data. The data presented in Appendix C is referenced in the wind axis with the tail off. The following conversion was used to convert the data from the wind access to the body axis:

$$\begin{bmatrix} fx \\ fy \\ fz \end{bmatrix} = \begin{bmatrix} \cos a & 0 & -\sin a \\ 0 & 1 & 0 \\ \sin a & 0 & \cos a \end{bmatrix} \begin{bmatrix} \cos b & -\sin b & 0 \\ \sin b & \cos b & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} -C_D \\ -C_Y \\ -C_L \end{bmatrix}$$

$$\begin{bmatrix} Mx \\ My \\ Mz \end{bmatrix} = \begin{bmatrix} \cos a & 0 & -\sin a \\ 0 & 1 & 0 \\ \sin a & 0 & \cos a \end{bmatrix} \begin{bmatrix} \cos b & -\sin b & 0 \\ \sin b & \cos b & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_R \\ C_M \\ C_N \end{bmatrix}$$

The tail off data was used because using the fuselage data with the tail on there would be no need to include the empennage flight surfaces in the FLIGHTLAB model.

2. Stabilizers

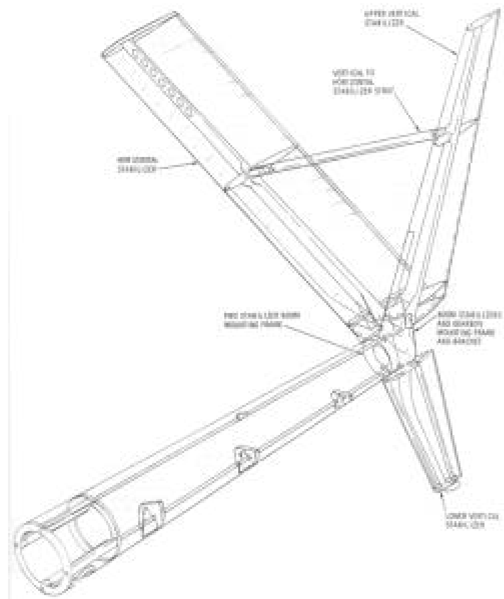


Figure 27: Stabilizers (From Ref 6.5)

a. Horizontal

Providing some longitudinal stability during forward flight, the horizontal stabilizer, a 67-inch NACA 0015 airfoil section with a constant 16.5-inch chord and maximum thickness of 3 inches, is attached to the starboard side of the tailboom at a dihedral angle of 25 degrees. An airfoil shaped stabilizer strut is attached between the upper vertical and the horizontal stabilizers to provide structural support for the horizontal stabilizer. This strut was not modeled in FLIGHTLAB.

b. Upper Vertical

The vertical stabilizers aid in minimizing yaw and provide lateral stability during forward flight. The upper vertical stabilizer is swept back 24 degrees and has a 5-

degree twist to improve tail rotor neutral position during cruise. It has a span of 50 inches and is formed by combining two different types of airfoil. The root airfoil is a NACA 0020 modified airfoil section with a root chord of 14.2 inches and maximum thickness of 3 inches and the tip airfoil is a NACA 0011 airfoil section with a tip chord of 7.13 inches and maximum thickness of 0.7 inches. (Ref 6.4) A twist in a lifting surface cannot be modeled in FLIGHTLAB so the twist was approximated as a 2.5-degree incident. Also, the two airfoil sections were modeled as a single NACA 0015 airfoil section since a complete wind tunnel test has never been conducted on either of the airfoil shapes.

c. Lower Vertical

The lower vertical stabilizer is a 12.5-degree swept NACA 63_3-018 modified airfoil section with a 12-inch cord and maximum thickness of 2 inches at the root and a 6-inch chord with a maximum thickness of 1 inch at the tip. It has a total span of 27.4 inches. (Ref 6.4) The lower vertical stabilizer was also modeled as a NACA 0015 airfoil.

3. Landing Gear

The landing gear consists of a pair of tubular aluminum alloy skin runners attached to the aircraft through struts, fairings, braces, and oleo shock dampers. The dampers cushion the upward and downward movement of the skids, while the forged aluminum alloy braces limit the forward movement and preventing shearing of the gear and skid alignment with the struts. The amount of damping provided by the blade and landing gear dampers is dictated by requirements to eliminate ground and air resonance instability. The skids both pivot and the fairing telescopes in a hollow fillet as the damper assemblies extend and retract. The landing gear dampers are approximately 12.21 inches long when extended and 8.96 inches long when compressed. The dampers assemblies are sealed hydraulic shock struts that are charged with 55-psi of nitrogen. The data for the landing gear was adapted from the work conducted by Dr. Rob King of Mississippi State University using an OH-6A and a ground resonance analysis conducted by Hughes Tool Company. (Ref 6.13, 6.14)

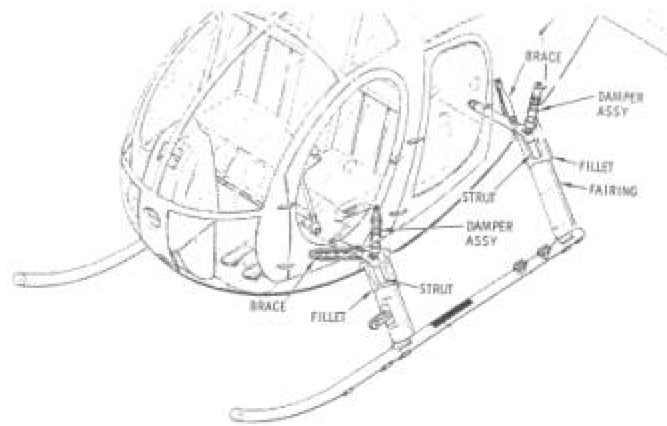


Figure 28: Landing Gear (From Ref 6.5)

D. CONTROL SYSTEM

1. Primary Flight Control System

The flight controls of the OH-6A are simple mechanical. The pilot primarily controls attitude, heading, forward speed, and rate of descent/climb of the aircraft via throttle and bell cranks. The flight control system consists of dual cyclic, collective and anti-torque pedals. The cyclic incorporates a 5 position, electronically operated trim actuator that varies the spring tension of the cyclic pitch control linkage. The OH-6A does not employ a false pitch bias thus the neutral point in a hover is approximately the same position as in forward flight. A manual friction adjustment ring controls the friction of the collective. The pilot can vary the amount of effort required to raise and lower the collective as well as increase the collective's resistance to move due to changes in the main rotor collective forces. The Cayuse has neither a hydraulic boost capability nor a stability augmentation system (SAS) to assist the pilot in controlling the aircraft.

The cyclic and collective pitch motions of the rotating swashplate are transmitted to pitch change horns via the pitch change rods. The rotating swashplate is driven by links connected to the hub. It is also connected to the non-rotating swashplate through a double row ball bearing with the outer race of the bearing being a part of the rotating swashplate and the inner race part of the non-rotating swashplate. The non-rotating swashplate tilts on a self-lubricated bearing surface that moves against the main rotor mast. Swashplate rotation is prevented by the links that transmit control motion from the mixer assembly. The cyclic and collective are connected to the mixer assembly via control rods.

The directional control of the aircraft is provided by the tail rotor control system. Depressing either anti-torque pedal moves a series of bell cranks and pushrods that travel through the tailboom to the tail rotor assembly. Pushrod movement actuates the pitch control assembly which consists of pitch change links connecting the pitch control arms to a swashplate that slide axially on the tail rotor transmission output shaft.

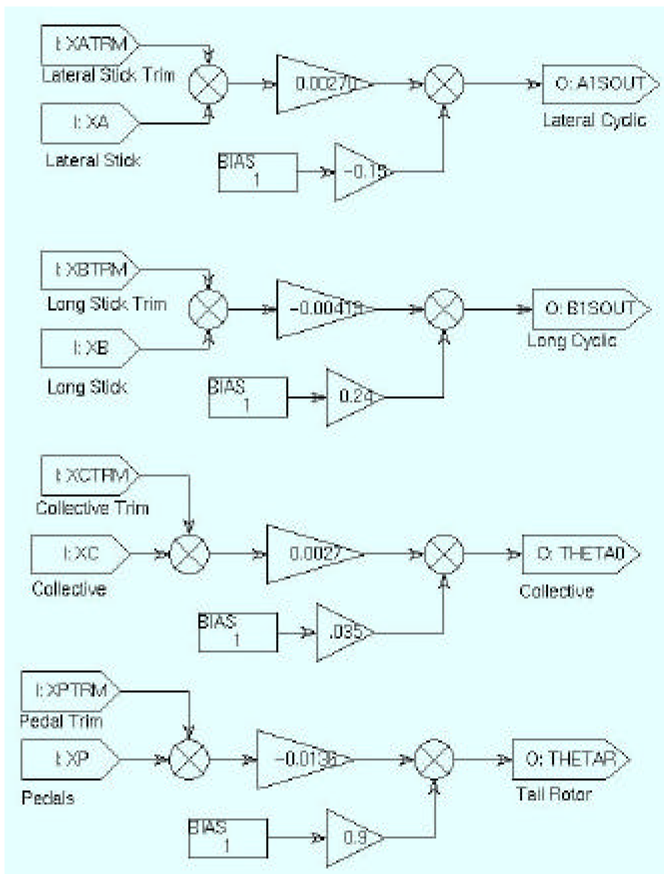


Figure 29: OH-6A control rigging in CSGE

The flight controls of the OH-6A were modeled in CSGE as depicted in Figure 29. Since there is virtually no cross coupling between the flight controls each control channel was modeled separately. The inputs to the controller are: Cyclic Lateral Perturbation (XA) and trim (XATRIM – initial condition), Cyclic Longitudinal Perturbation (XB) and trim (XBTRIM – initial condition), Collective Perturbation (XC) and trim (XCTRIM – initial condition), and Pedal Perturbation (XP) and trim (XPTRIM

– initial condition). The controller outputs are: Main Rotor Swashplate Lateral Cyclic Angle (A1S), Main Rotor Swashplate Longitudinal Cyclic Angle (B1S), Main Rotor Swashplate Collective Angle (Theta1), and Tail Rotor Swashplate Collective Angle (Theta2).

The slope of the rigging curves were provided by Mr. Mike Mosher of NAVAIR while the bias of the control rigging was determined via model comparison against flight test data. Appendix D is a graphical representation of the flight control rigging curves. The slopes and biases are:

Long Stick position (%) → -.24 deg/% (linkage) + 13.75 deg→ B1s (deg)

Lat Stick position (%) → .155 deg/% (linkage) - 8.59 deg→A1s (deg)

Pedal position (%) → -.78 deg/% (linkage) + 2 deg→ Theta t/r (deg)

Long Stick position (%)→ .155 deg/% (linkage) + 51.56 deg→ Theta m/r (deg)

2. Higher Harmonic Control (HHC)

In a helicopter, low vibration levels will reduce structural fatigue of the airframe, rotor system, and drivetrain as well as increase passenger and crew comfort levels. The conventional means of reducing helicopter vibrations is through passive systems such as vibration isolators, vibration absorbers, bifilar or Frahm absorbers that treat the vibratory loads after they have been generated. An active system generates high frequency pitch motion on the rotor blades to suppress the vibratory aerodynamic forces that act on the rotor blades and are transmitted to the airframe. Active systems are classified as either an Individual Blade Control (IBC) or a Higher Harmonic Control (HHC) system. As the name implies, an IBC system uses a computer to control the movements of each individual blade via pitch links whereas an HHC system controls the rotor system via the movements of the swashplate. Recent studies indicate that the use of on-blade control surfaces such as smart materials (piezoceramics) can produce vibration reductions comparable to swashplate-based HHC but for less power.

In 1982 Hughes Helicopters, Inc., under contract with the U.S. Army and NASA, conducted flight tests of an active HHC equipped OH-6A. Pitch, roll and collective motion of the stationary swashplate are provided by three electro-hydraulic high frequency servo-actuators. The actuators replace the rod-end links between the control mixer and the stationary swashplate and utilize 3000-psi hydraulic power for servo actuation. To prevent unwanted feedback to the cockpit flight controls the OH-6A was modified with a 1500-psi boost system for the primary flight controls. The individual actuators have a total stroke of 0.20 inches at 32 Hz (4/rev of the OH-6A), which translate to a collective blade angle authority of ± 2 degrees.

The operation of the HHC system is relatively straightforward. Tri-axial accelerometers mounted below the pilot's seat sense the vertical, lateral and longitudinal vibrations and pass these signals to an electronic control unit (ECU) that converts the analog signal into a digital signal and separate the sine and cosine 4/rev components of vibration which is read by a computer. The computer, which contains the mathematical model for zeroing the vibrations, analyzes the input and determines the proper feather required to cancel the vibration. This result is then sent back to the ECU which provides the signal to the servos to drive the stationary swashplate. Collective motion of the stationary swashplate at 4/rev results in 4/rev pitch motion of the rotor blades and 4/rev pitch and roll motion produces 3/rev and 5/rev pitching of the blades. This process is updated approximately every two rotor revolutions (163-267 msec) to permit rapid updating of the system during maneuvers. The update time includes the actual computation time (58-162 msec depending on algorithm used) and a waiting period (105 msec), which provides enough time for the rotor to respond to the control inputs and for the effects to be felt in the airframe.

E. ENGINE

The OH-6A was originally fielded to use either an Allison T63-A-5A or T63-A-700 engine. Both engines are dynamically similar and each incorporates a multi-stage axial-centrifugal compressor, a single combustion chamber, a two-stage gas producer turbine, and a two-stage power turbine. The engine has a dry sump type lubrication system with an external oil tank and oil cooler and is mounted at a 43-degree nose up attitude. The engine incorporates a compressor acceleration bleed air system to provide rapid engine response during starting and acceleration.

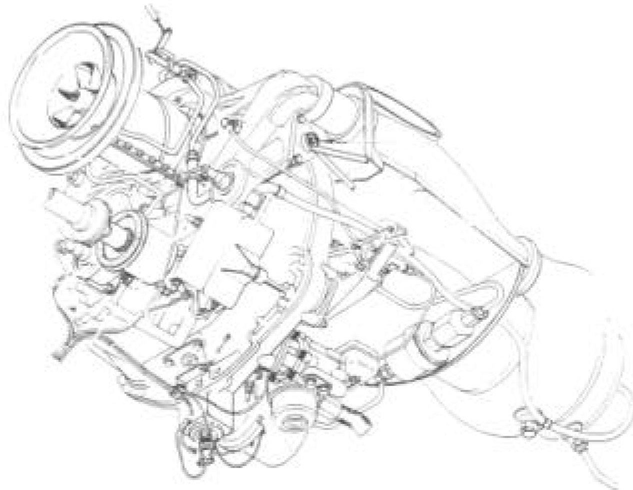


Figure 30: Allison T63-A-5A (250-C17) (From Ref 6.5)

Due to proprietary details required by FLIGHTLAB to model an engine, the Allison engine was not modelled. Instead, a generic ideal model was used.

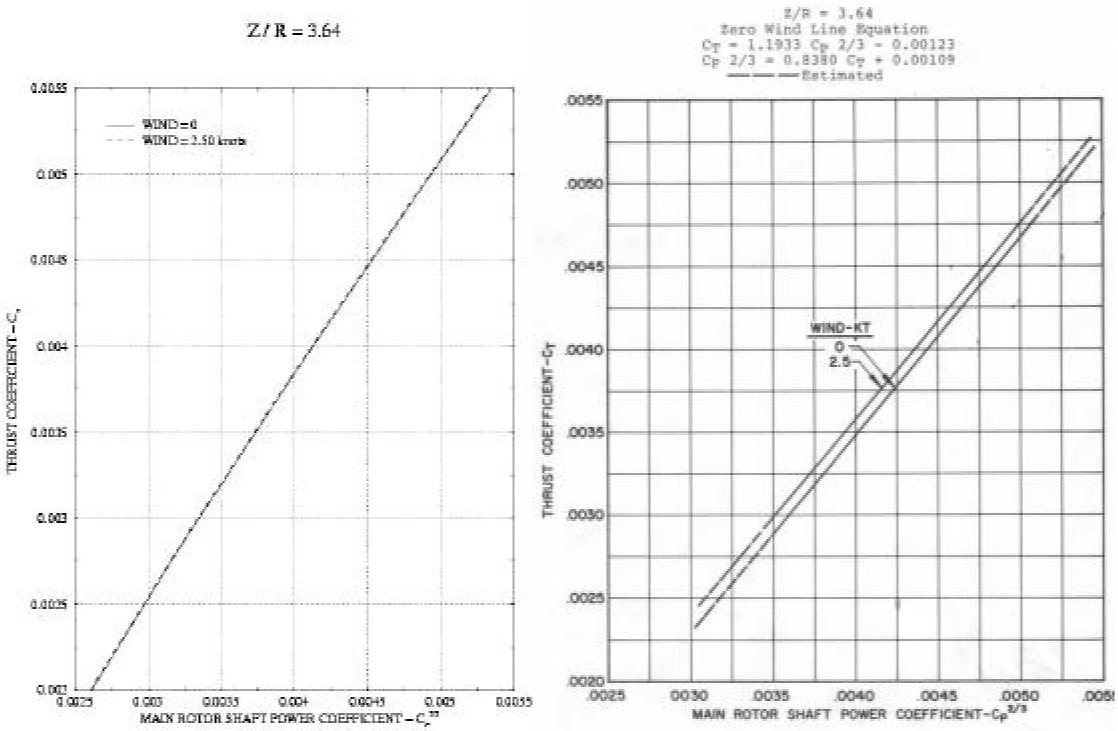
F. MODEL VALIDATION

The OH-6A model was validated against flight test data gathered by NAVAIR during the LOH competition. (Ref 6.23) A side-by-side comparison is presented in the following section with the FLIGHTLAB results labeled (a) and the NAVAIR results labeled (b). Dr. Hong Xin of ART assisted in writing Scope scripts to run the various tests (Appendix G). The OH-6A model was modified slightly to match the design that was flown during the evaluation. The modifications were:

1. Horizontal Stabilizer canted 30 degrees vice 25 degrees.
2. Main rotor speed 470 rpm vice 483 rpm.
3. Ideal engine (constant main rotor rpm) vice T63-A-5A.

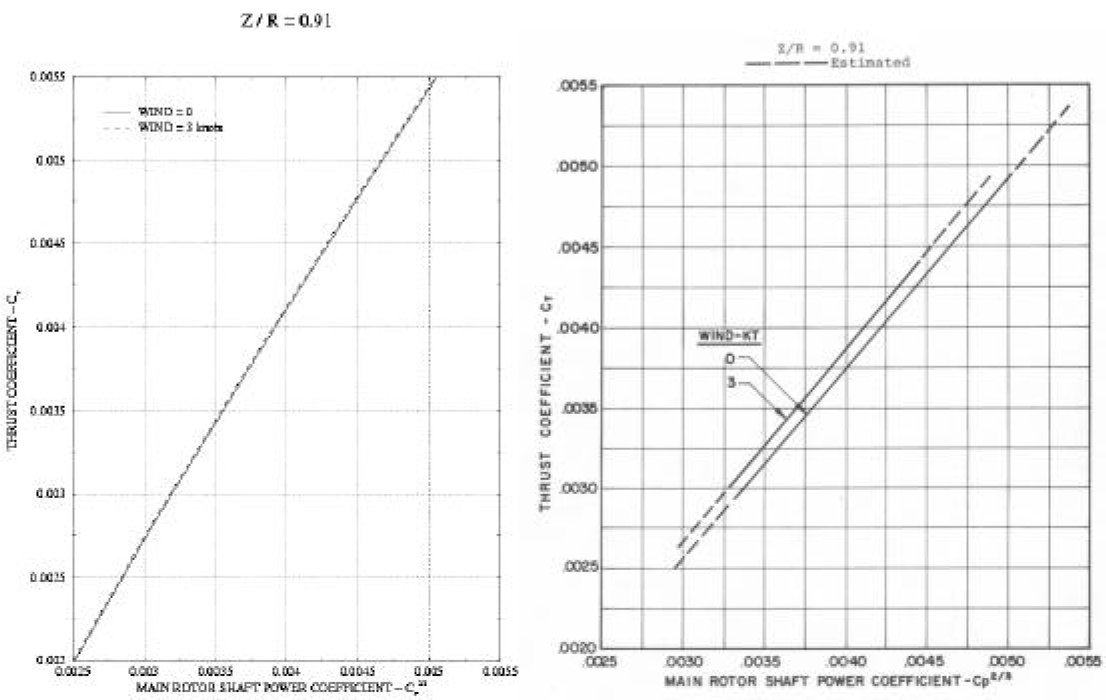
1. Hover Performance

The hover performance was conducted for hover conditions in and out of ground effect. The aircraft gross weight was swept from 1100 lb_m to 3300 lb_m and the aircraft was trimmed in a hover using the hover analysis utility of Xanalysis.



a) FLIGHTLAB b) NAVAIR

Figure 31: OGE Hover Performance (From Ref 6.23)



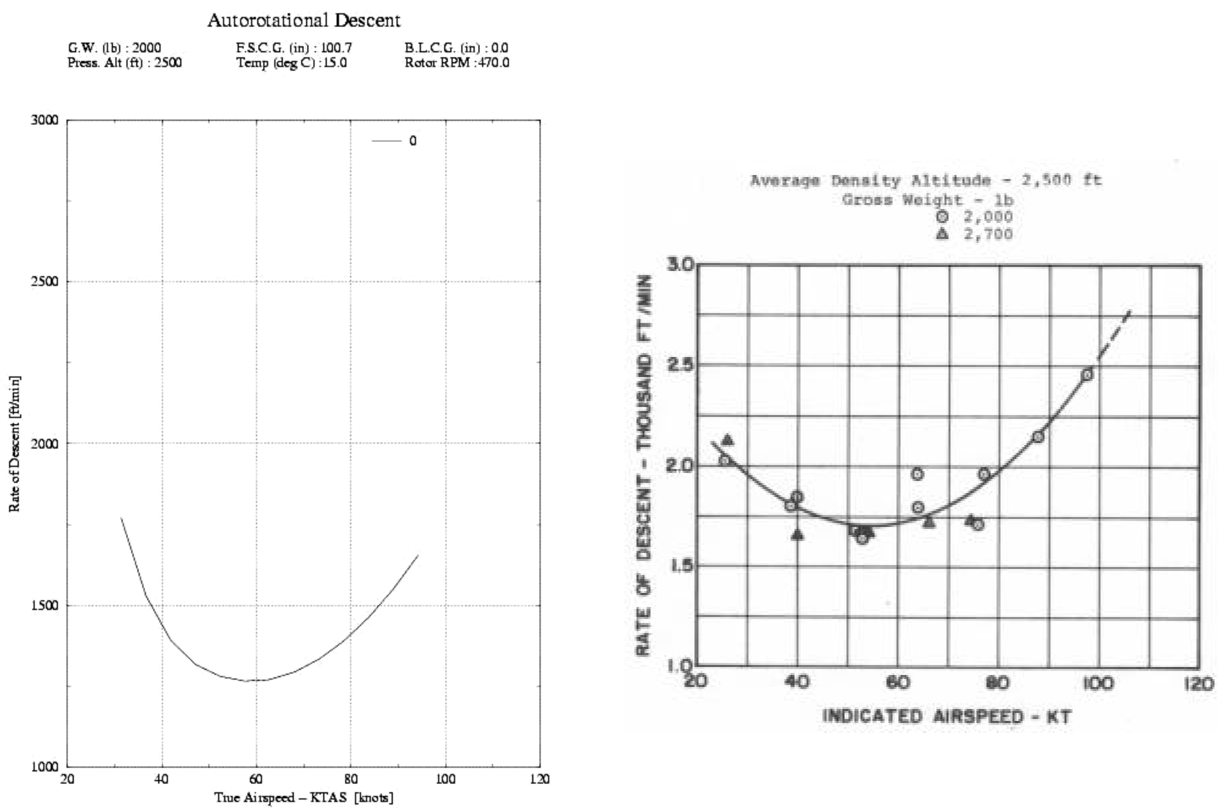
a) FLIGHTLAB b) NAVAIR

Figure 32: IGE Hover Performance (From Ref 6.23)

FLIGHTLAB C_T values for a given $C_P^{2/3}$ and resulting slopes are within 15% of the NAVAIR results. Variations due to wind are not as obvious in the FLIGHTLAB analysis.

2. Autorotation

Steady-state autorotations with main rotor speed of 470 rpm were performed at gross weights of 2000 lb_m and 2700 lb_m through airspeeds of 30 KIAS to 90 KIAS. The minimum rate of descent was 1550 fpm at 58 KIAS at 2000 $lb_{m.}$ The autorotation computed in the NAVAIR test was conducted at a main rotor speed of 500 rpm yielding a minimum rate of descent of 1710 fpm at 55 KIAS at 2000 lb_m. The 470-rpm main rotor speed was used in the FLIGHTLAB analysis due to the limitations of using an ideal engine model; main rotor rpm is always set at 100% and to reach 500 rpm the collective must be set at –3% which is unrealistic.

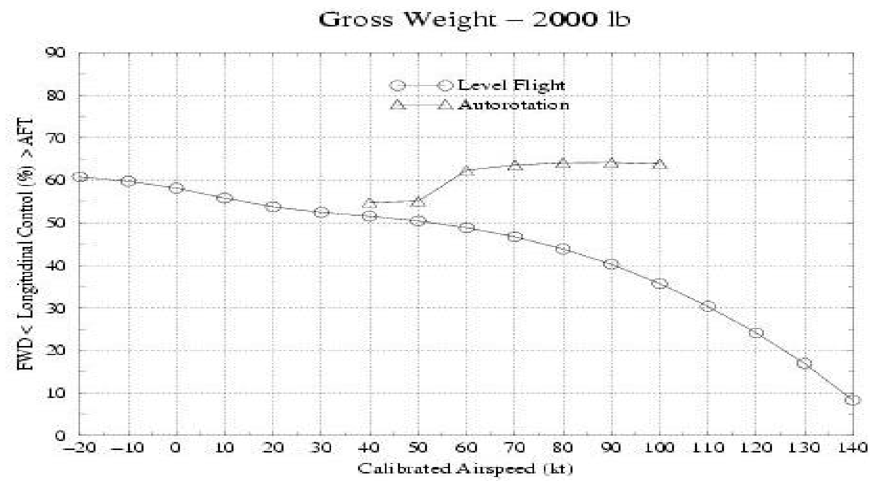


a) FLIGHTLAB b)NAVIAIR

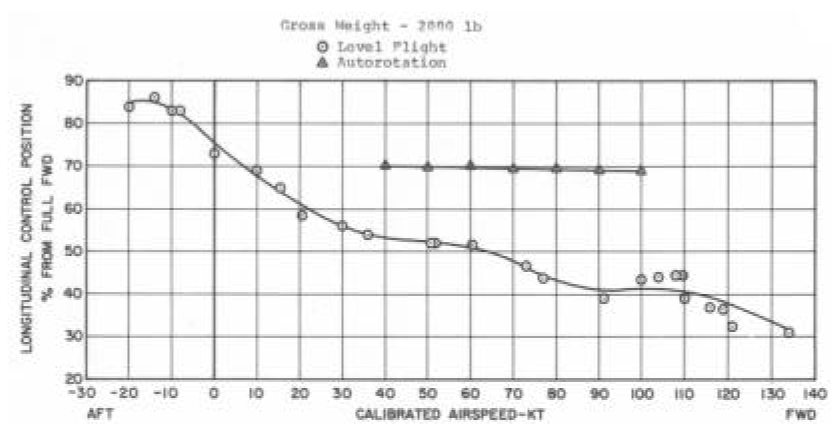
Figure 33: Autorotative Rate of Descent (From Ref 6.23)

3. Level Flight Performance

Varying the airspeed of the aircraft from forward flight to rearward flight and then in various speeds of autorotation and measuring the position of the longitudinal control stick reproduced the level flight performance chart. The control positions follow the same general trends but positions are off by about 10% for a given airspeed.



a) FLIGHTLAB

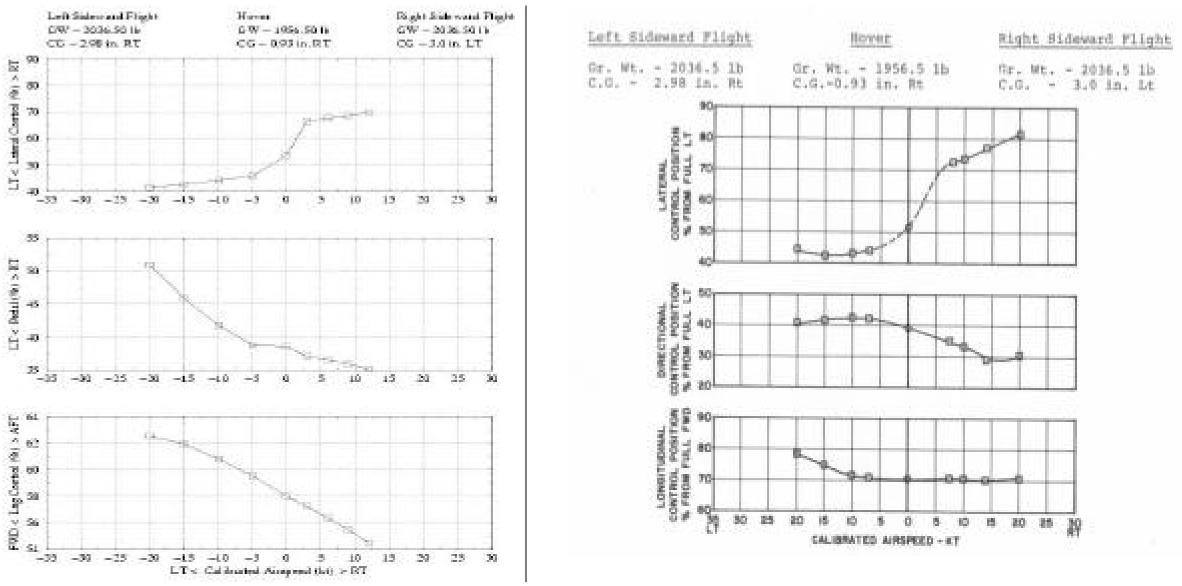


b) NAVIAR

Figure 34: Level Flight Performance (From Ref 6.23)

4. Sideward Flight

The sideward flight characteristics were determined by measuring the flight control positions for various speeds of sideward flight. The control positions follow the same general trends but positions are off by about 10% for a given sideslip.

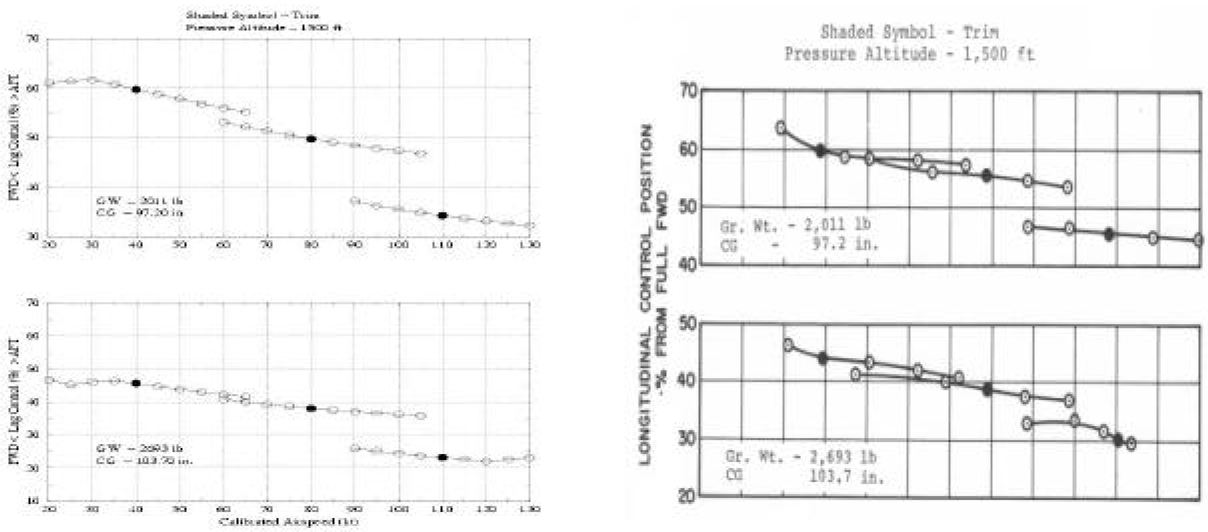


a) FLIGHTLAB b) NAVAIR

Figure 35: Sideward Flight (From Ref 6.23)

5. Static Longitudinal Stability

Varying the airspeed around a trimmed longitudinal stick position and observing the stick position produced the static longitudinal stability results. Results from two different gross weights, 2011 lbm and 2693 lbm, correlate directly with the expected NAVAIR results.

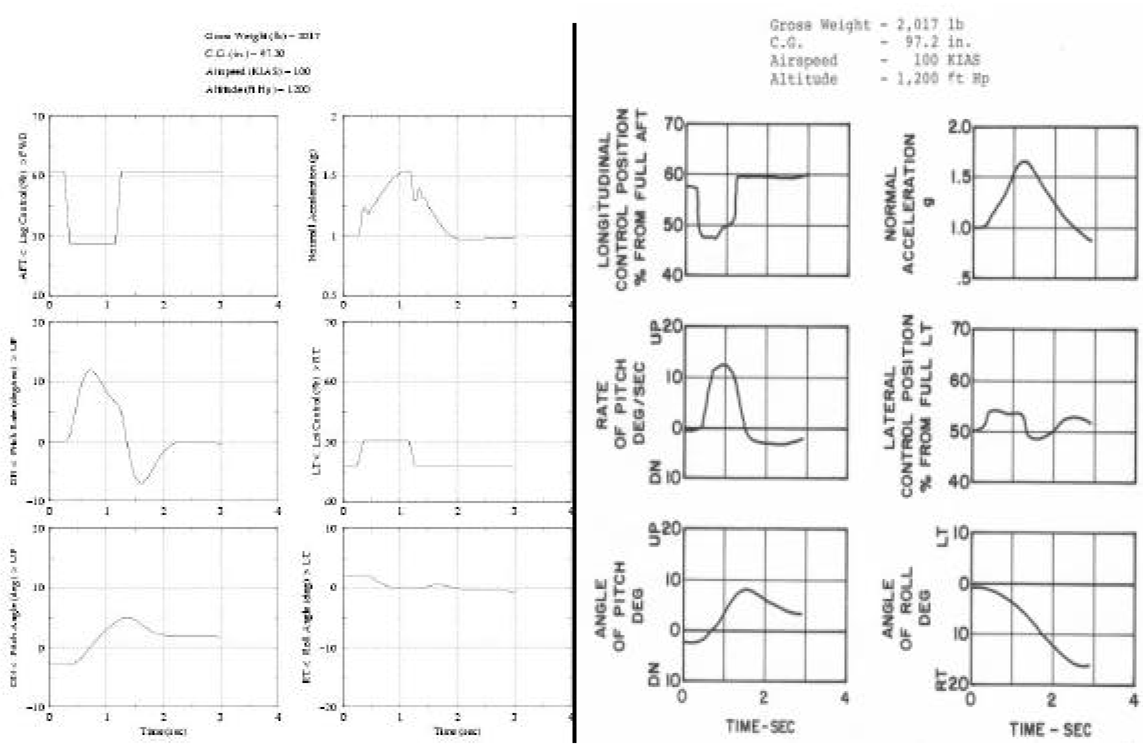


a) FLIGHTLAB b) NAVAIR

Figure 36: Static Longitudinal Stability (From Ref 6.23)

6. Dynamic Longitudinal Stability

A 12% step input was generated in the longitudinal control and a 4% step input was generated in the lateral controls to reproduce the dynamic response test performed in the NAVAIR analysis. The results correlate well with each other. The FLIGHTLAB model is slightly more responsive to disturbances than an actual OH-6A. Note that there is an angle of roll at the beginning of the FLIGHTLAB test that cannot be explained at this time.

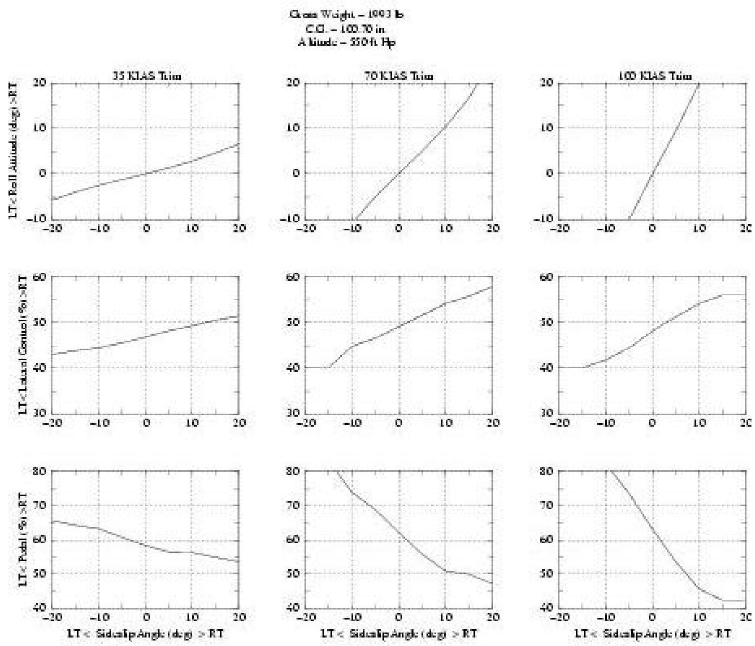


a) FLIGHTLAB b) NAVAIR

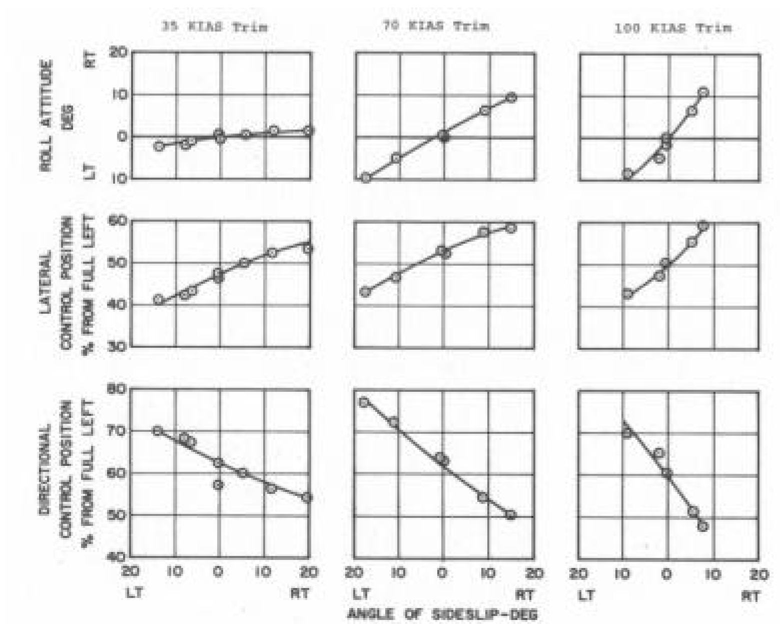
Figure 37: Dynamic Response to Longitudinal Control Input (From Ref. 6.23)

7. Static Lateral-Directional Stability

The Lateral response of the lateral-directional stability was determined by varying the sideslip of the aircraft for a set airspeed and measuring the control positions and roll attitude. The FLIGHTLAB model controls tend to move a greater distance to maintain the same airspeed and sideslip than the actual OH-6A but the trend of movement is consistent.



a) FLIGHTLAB

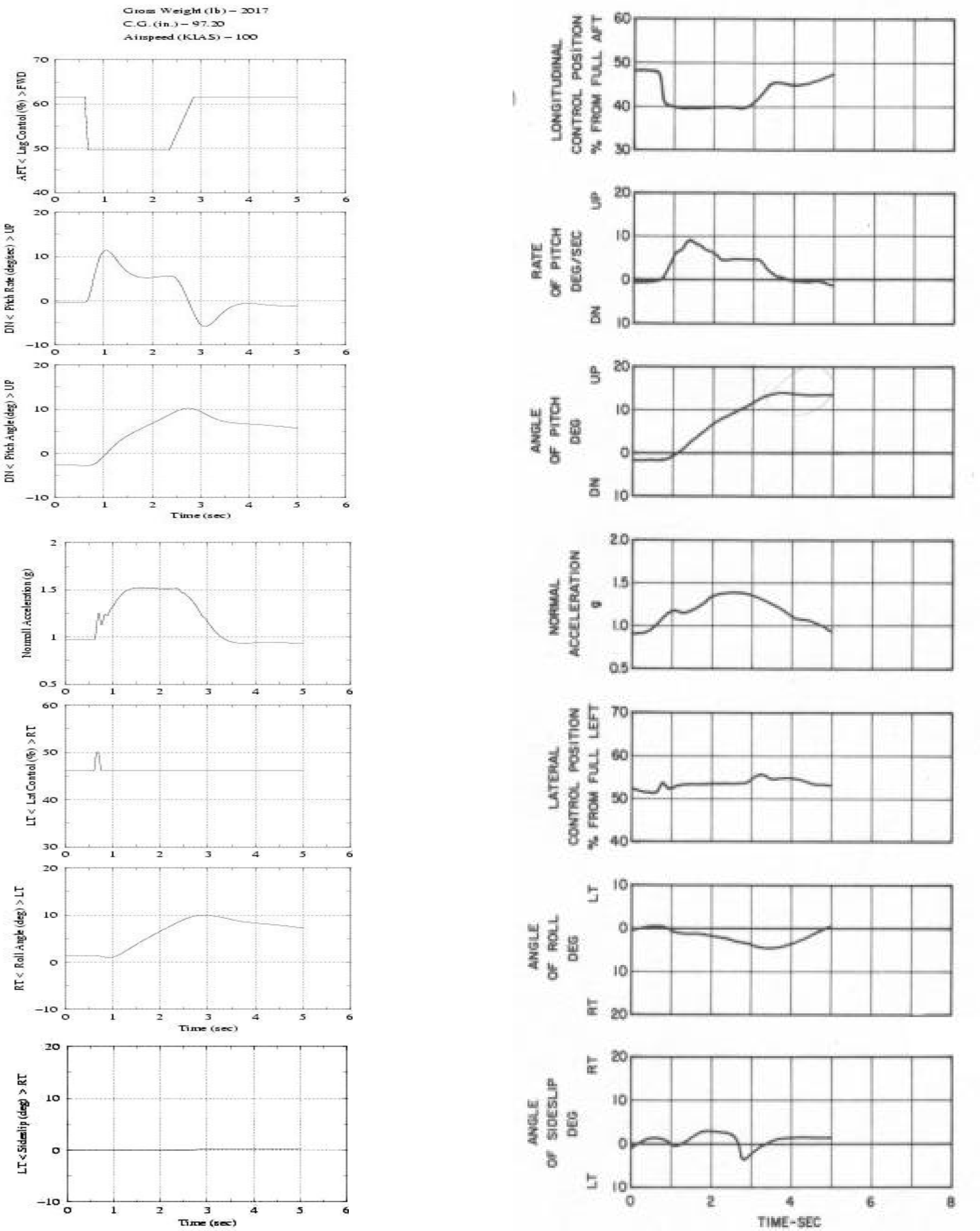


b) NAVAIR

Figure 38: Static Lateral / Directional Stability (From Ref. 2.63)

8. Maneuver Stability

Generating a step input into the longitudinal control and measuring the response reproduced maneuver stability. The trend of the measured results correlate to what is expected except roll angle which diverges instead of returning to zero.

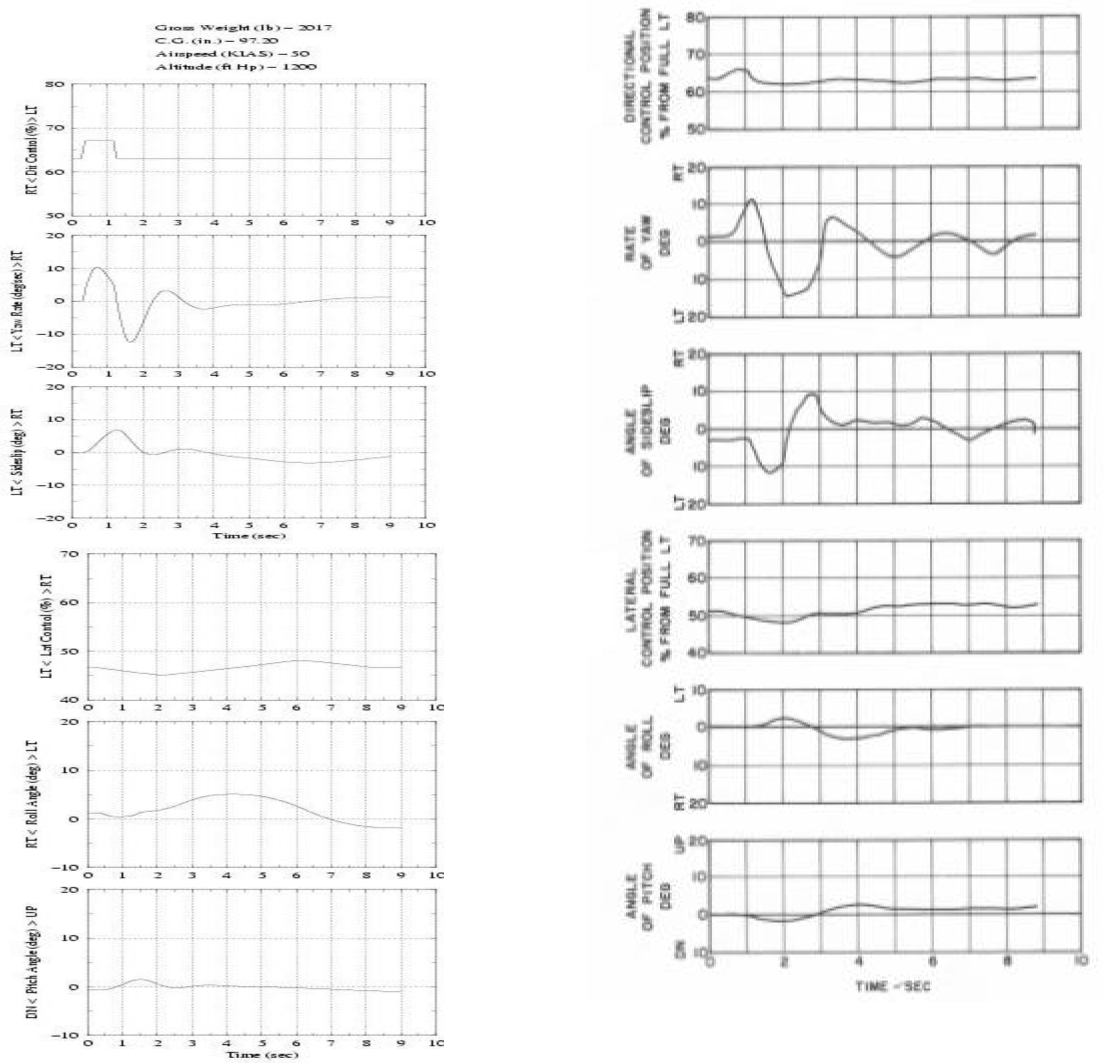


a) FLIGHTLAB b) NAVAIR

Figure 39: Maneuvering Stability (From Ref 6.23)

9. Dynamic Response to Directional Pulse Input

A small step input was generated in the directional control pedals while the aircraft was flying at 50 knots and various responses were measured.



a) FLIGHTLAB b) NAVAIR

Figure 40: Dynamic Response to Directional Pulse Input (From Ref 6.23)

10. Observations

Overall, the FLIGHTLAB model operates like the real OH-6A. The lateral control positions at high speed and in sideward/rearward flight above 10 knots were not accurate which produced inaccuracies in the roll angle and roll rates in those regimes. The errors produced are possibly due to the extrapolation of the forces and moments of the fuselage where wind tunnel tests data does not exist.

VII. CONCLUSION

A. H-60 SIMULATORS

Current military helicopter flight simulators use hydraulic ram motion platforms that are capable of producing frequencies up to approximately 6 Hz. The minor improvement in flight fidelity does not justify the prohibitive costs to increase the bandwidth above 6 Hz. To make up for the slow response of the hydraulic motion base, several military flight simulators (MH-53E, UH-3H) incorporate electric seat-shakers to simulate the higher frequency problems like rotor damper malfunctions and erratic SAS inputs to the rotor.

The MH-60S Tactical Operational Flight Trainer (TOFT) uses only motion seats; there is no motion platform (the cab sits on the deck). Unfortunately, motion seats alone cannot produce the large-motion cues that can be generated from a motion platform and motion platforms cannot produce the small-motion vibration, surface and turbulence cues that can be produced with the motion seat without damage to the simulator and excess power requirements. By combining a motion platform with a motion seat both objectives can be obtained. This concept is being developed by NAVAIR for incorporation in the next version of the MH-60R Weapon System Trainer (WST). The MH-60R WST will capitalize on the recent advances in visual displays, motion platforms, and control loaders. It is currently slated to incorporate a hydraulic ram motion platform due to advancements in synthetic oils and hydraulic seals to minimize the negative aspects common to the use of hydraulic fluids and the inadequacy of electromagnetic rams to support the loads required. The visual displays will be the Evans and Sutherland Harmony Image Generator with a Panorama 200 degree by 40 degree fully collimated display surface permitting either side to fly with no adverse difference in perception of motion cause by seat position. Wide Area Collimated windows will expand the field of view to add an additional viewing capability out the lower side windows. It is a wrap-around system, but the chin bubble windows have been moved to permit viewing down and aft at approximately the pilot and copilot shoulders. The control loaders and motion seat will be electromagnetic ram driven to capitalize on their efficiency and broad bandwidth capabilities. The helicopter flight dynamic model will be a new Blade

Element Model coded in C++ and based upon the MH-53 Blade Element Model (BEM) that was coded in Ada. The previous FORTRAN model currently in use in other H-60 flight simulators will not be used because the BEM is more physics-based and expandable for future modifications. FLIGHTLAB can be used as an alternate to the BEM being developed for the MH-60R. Experiments using FLIGHTLAB in a UH-60A OFT at Fort Ord (prior to BRAC) have proven that it can be used as the primary flight dynamics model in a military flight simulator. The distinct advantage of using a development suit like FLIGHTLAB is that it has the generality required to produce modular, reusable modeling components where a functional modeling approach like the BEM is highly dependent on the available data test set. FLIGHTLAB's use of Multi-body Dynamics solution methods eliminates the need to manually derive and program coupled equations; a rotorcraft model may be assembled from a predefined library of modeling elements that generically represent rotorcraft phenomena and subsystems. (Ref 7.1)

B. RECOMMENDATIONS FOR FURTHER RESEARCH

The modeling and analysis conducted on the OH-6A yielded good results. FLIGHTLAB offers several options to enhance the fidelity of the model.

1. First, the main rotor could be modeled as a Finite Element or discrete mass model. Some of the data for this type of model was provided with the DART model, yet other data such as blade mass radius of gyration need to be determined. Also, a deeper investigation into the blade vibratory modes and blade dampers will need to be conducted.

2. Next, the engine should be modeled as a Turboshaft Engine. Much of the details of the engine are proprietary to Rolls Royce but ART or NPS should look into forming a cooperative agreement with Rolls Royce to obtain the needed data. The Naval Test Pilot School flies TH-6Bs that have Allison C250-30 engines installed without an improved drivetrain or transmission so the exact model of the Allison C250-17 engine is not a requirement.

3. FLIGHTLAB offers a way to conduct real time design and analysis of a Higher Harmonic Control (HHC) or Individual Blade Control (IBC) system. Dr. Bob Wood and Dr. Mike Spencer, both from NPS, have worked extensively with adapting a

HHC algorithm. Dr. Wood's work was implemented in an OH-6A in 1982 while Dr. Spencer's Neural Network approach has yet to be flown. This will require users to develop their control algorithms in C and recompile the Scope environment, as the current iteration of FLIGHTLAB does not include a feature to build a user defined function block, similar to a ".m" file used in SIMULINK.

4. Advanced Rotorcraft Technologies, Inc. is developing several new capabilities into their FLIGHTLAB modeling suite as part of several SBIR projects with NASA and NAVAIR. Major emphasis has been on modeling the capability of the H-60 to perform minesweeping missions, developing a ship airwake model to demonstrate the interaction between a helicopter and a ship in order to aid in the expansion of flight envelope evaluations, developing airwake interactions between multiple aircraft in a shipboard environment, and also in the implementation of the V-22 flight control system in FLIGHTLAB to assist in the development of improved control algorithms. NPS students with past experiences in these flight regimes and strong engineering backgrounds would provide valuable insight into the development of these models.

5. Students in the helicopter or aircraft design class could benefit from using FLIGHTLAB to evaluate their designs. ADS-33 evaluations as well as limited TPS flight profiles built into Xanalysis would add another element of realism to the design experience.

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APPENDICIES

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APPENDIX A. FAA REGULATIONS

A. BACKGROUND

The complexity, operating costs, and operating environment of modern aircraft combined with advancing technology in flight simulation have lead to expanding use of flight training devices and aircraft simulators in the training and evaluation of flight crewmembers. Flight simulation provides a safe and effective environment for the instruction, demonstration and practice of certain maneuvers and procedures associated with a particular aircraft or crewmember position. Modern aircraft simulators can provide a more exhaustive training regime than can be accomplished in an aircraft. This training has been shown to provide a high transfer of learning and behavior from the simulator to the aircraft. (Ref A.2)

The FAA has traditionally recognized the value of training devices in the case of fixed wing aircraft. As technology has progressed and the capabilities of flight simulators has increased, Federal Aviation Regulations (FAR) have been revised to authorize credit for their use in the training and evaluation of crewmembers in *airplane* flight simulators. But to date, the FAR has not addressed the training and evaluation of aircrew in helicopter flight simulators. This has hampered their development and use. (Ref A.3) Helicopter simulators in use today have been evaluated and approved only on a case-by-case basis. For the future, technological advancements, aircraft complexity, higher operational costs, and other factors are expected to spur increased interest in helicopter simulators. Amendments of the applicable regulations in the FAR are expected to extend credit to the use of helicopter simulators in the training and evaluation of helicopter crewmembers. Until the time that the regulations are revised, the FAA issues Advisory Circulars (AC's) in order to provide guidance and information in a designated subject area or to show an acceptable method of compliance with a FAR (Ref A.3, Section 1) The contents of an AC are not mandatory unless incorporated into a regulation by reference. AC120-63 is specifically concerned with Helicopter Simulator Qualification and provides the acceptable means of qualifying a helicopter simulator used in training and evaluation of aircrew under various sections of the FAR.

B. HELICOPTER SIMULATOR

1. Definition

A Helicopter Simulator is defined as a full size cockpit replica of a specific type or make, model and series of helicopter. It includes the "assemblage of equipment and computer software programs necessary to represent the helicopter in ground and flight operations, a visual system providing a real time out-of-the-cockpit view, a control force system, and a motion cueing system that provides at least equivalent to that of a three degree-of-freedom motion system" (Ref A.3, Section 5.a) are required. Helicopter simulators are classified as Level A through Level D as defined in AC 120-63 appendix 1. Level A is reserved for potential future uses while Level B through Level D provide increasingly higher degrees of realism and fidelity.

A Convertible Simulator is a "simulator in which hardware and software can be changed so that the simulator can become a replica of a different model helicopter." (Ref A.3, Section 5.c) It is usually but not limited to being the same type of helicopter. A separate FAA evaluation is required for each model and series in which a convertible simulator can be reconfigured.

2. Evaluation Policy

The Helicopter Simulator must be assessed in those areas that are essential to accomplishing training and checking processes required by the FAR and by the sponsoring organizations approved training program. This includes the simulator's performance in all phases of flight as well as aerodynamic responses. Cockpit control and functions checks in addition to other requirements depending on complexity or qualification level of the simulator must also be evaluated to ensure proper operation. The appendices in AC 120-63 contain specific details (parameters, tolerances and flight conditions) of pilot acceptance tests and are evaluated by an FAA rated pilot qualified in the respective helicopter. Validation tests are used to objectively compare simulator and airplane data to assure that they agree within specified tolerances. Functions tests subjectively verify the correct operation of the simulator's controls, instruments and systems and they are also designed to provide a basis for evaluating the simulator's capability to perform the specified training evolutions. (Ref A.3, Sections 7.b-e)

The aircraft manufacturer's flight test data will normally be accepted for initial simulator qualification while an older aircraft may require additional flight-testing. A new type or model of helicopter may, for an interim period as determined by the FAA, use predicted data validated by the manufacturer's preliminary flight test data.

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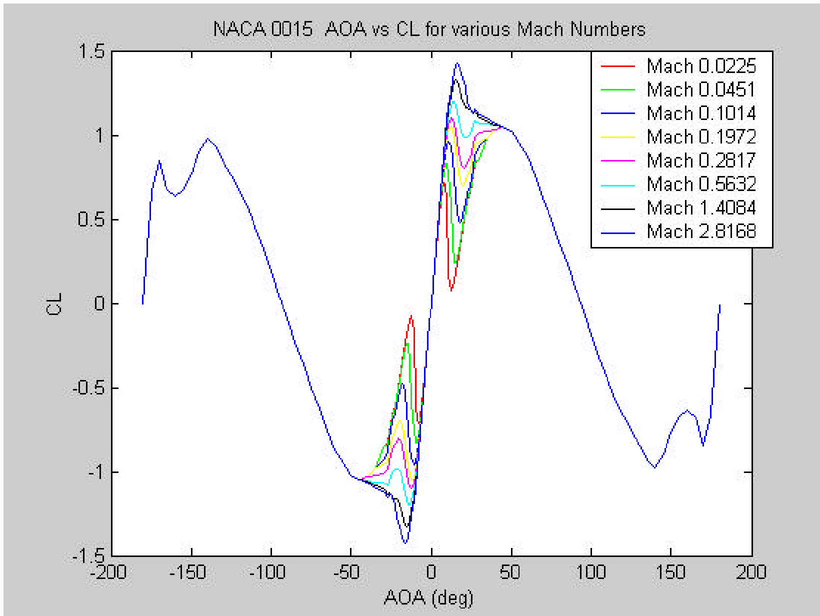
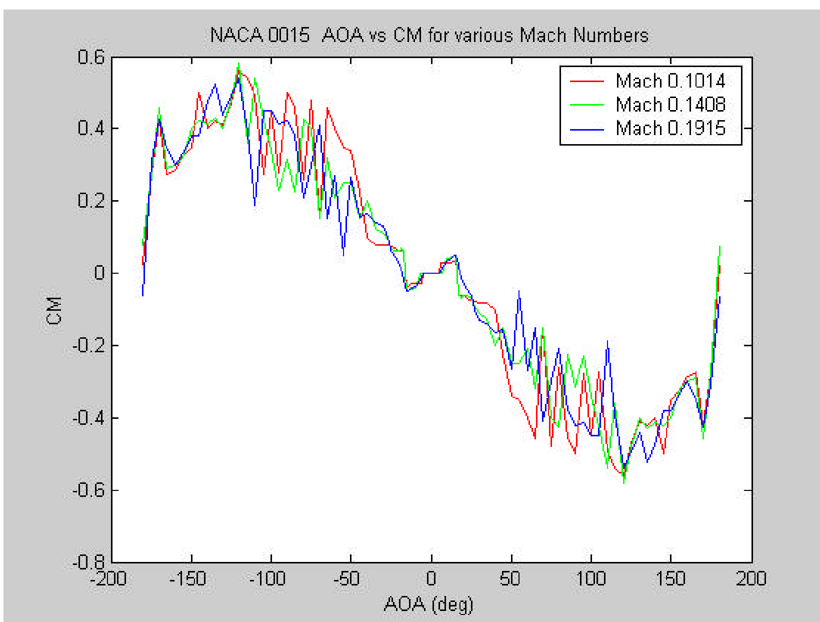
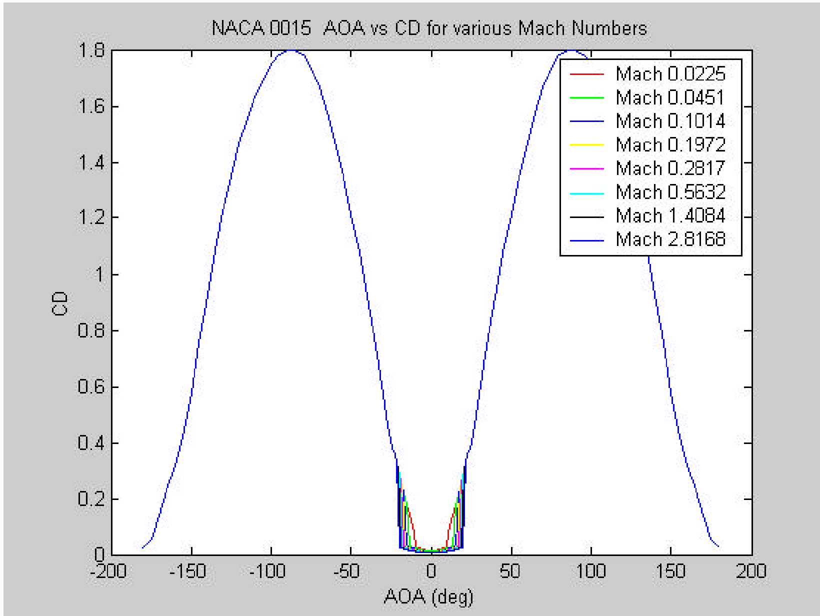
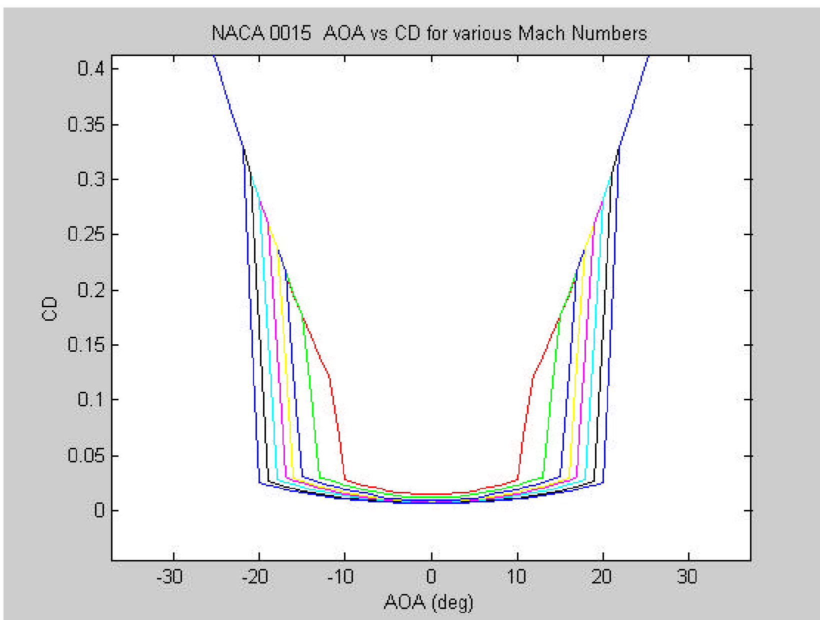
APPENDIX B. NACA 0015 AIRFOIL PROFILES







NACA 0015 AOA vs CD for various Mach Numbers
Mach 0.0225
Mach 0.0451
Mach 0.1014
Mach 0.1972
Mach 0.2817
Mach 0.5632
Mach 1.4084
Mach 2.8168
CD
AOA (deg)



NACA 0015 AOA vs CD for various Mach Numbers
CD
AOA (deg)

APPENDIX C. MAIN ROTOR BLADE DART INPUTS

The basic hub parameters for both rotors are shown below:

Parameter	369C	369D/E
Radius (in.)	157.63	158.12
Flap Hinge (in.)	5.5	6.0
Lag Hinge (in.)	16.188	16.688
Blade Attach. (in.)	17.188	17.688
Pitch Arm Length (in.)	6.06	6.06
Pitch Arm Radial Sta. (in.)	5.5	6.0
Rotor Speed (RPM)	483	492
Shaft Tilt (deg., + fwd)	3.0	3.0
Delta 3 (deg.)	0.0	0.0
Precone (deg.)	0.0	0.0
Flap Damping (in.-lb-sec.)	0.0	0.0
Torque Offset (in., + aft CL)	.375	.375
Lag Damper Stiffness (in-lb/rad.)	0.0	17,000

The distributed blade and pitchcase parameters are listed in input form from DART. The properties are listed as radius (in.), value, radius, value, etc. For blade weight, Xcg, Ic, and Ib, the properties are assumed constant between the station locations. For all other properties, the values vary linearly between stations. The property descriptions are:

BMASS	Blade running weight	lb/in
XCG	Blade chordwise C.G., inches aft of C/4 (1.7075” from leading edge)	inches
IC	Blade chordwise inertia about C.G.	lb-in^2/in
IB	Blade beamwise inertia about C.G.	lb-in^2/in
EIF	Blade flapwise stiffness	lb-in^2/10^6
EIC	Blade chordwise stiffness	lb-in^2/10^6
GJ	Blade torsional stiffness	lb-in^2/10^6
XSC	Blade shear center., inches aft of C/4 (1.7075” from leading edge)	inches
CHORD	Blade chord length	inches
TWIST	Blade built-in twist	degrees, + nose up

DART Input

```
BMASS     2    1.0    .0025907
   6.0   1.0013    7.0    .3413    8.0    .3486    9.0    .2953   11.0    .3016   13.0   .4016
  14.0    .3016   15.0   1.3443   16.0   2.6593   17.0   1.7613   18.0    .3766   19.0   .4293
  20.0    .6945   22.0    .7245   22.0    .792    23.0    .1786   24.0    .2145   25.0   .1795
  27.0    .1385   37.0    .1349   91.0    .1359  122.0    .1547  128.0    .1533  129.0   .1592
 139.0    .1612  140.0    .1619  141.0    .1599  146.0    .1792  150.0    .2022  151.0   .2052
 152.0    .4232  153.0    .4162  154.0    .3751  156.0    .4411  157.0    .5441  158.0   .0430
 158.13

XCG       2
   6.0   0.0       7.0   0.0       8.0    .0547    9.0    .0645   11.0    .0632   13.0   .0474
  14.0    .0632   15.0   2.3686   16.0   1.1973   17.0   1.8062   18.0    .0429   19.0   .4125
  20.0    .3108   21.0    .8201   22.0    .4207   23.0    .2670   24.0    .2334   25.0   .2906
  27.0   -.1058   37.0   -.1232   91.0   -.0851  122.0   -.1769  128.0   -.2025  129.0  -.1140
 139.0   -.1230  140.0   -.1257  141.0   -.1167  146.0   -.3804  150.0    .8604  151.0   .9143
 152.0   -.0881  153.0   -.0754  154.0   -.0359  156.0   -.0500  157.0   -.2333  158.0   .7233
 158.13

IC        2    1.0    .0025907
   6.0   7.945     7.0   0.6       8.0    .0595    9.0    .5825   11.0    .62     13.0   .625
  14.0    .625    15.0  15.0      16.0  16.01     17.0  15.74     18.0    .7847   19.0   .8945
  20.0   2.0839   21.0   2.8167   22.0   1.6624   23.0    .3780   24.0    .4540   25.0   .5175
  27.0    .3992   37.0    .3897   91.0    .4189  122.0    .4754  128.0    .4710  129.0   .4893
 139.0    .4953  140.0    .4975  141.0    .4912  146.0    .5506  150.0    .6213  151.0   .6304
 152.0    .8123  153.0    .7988  154.0    .7200  156.0    .8467  157.0   1.0444  158.0   .0825
 158.13

IB        2    1.0    .0025907
   6.0   0.6       7.0   0.6       8.0    .595     9.0    .5825   11.0    .62     13.0   .625
  14.0    .625    15.0   4.230    16.0   4.54     17.0   4.44     18.0    .0314   19.0   .0358
  20.0    .0579   21.0    .0604   22.0    .0356   23.0    .0081   24.0    .0097   25.0   .0106
  27.0    .0081   37.0    .0072   91.0    .0072  122.0    .0097  128.0    .0096  129.0   .0100
 139.0    .0101  140.0    .0102  141.0    .0100  146.0    .0112  150.0    .0127  151.0   .0129
 152.0    .0166  153.0    .0163  154.0    .0147  156.0    .0173  157.0    .0213  158.0   .0017
 158.13

EIF       1    1.0    1.0   +6
   6.0     23.1      8.0     19.8   10.0   17.0     12.0   14.5     14.0   12.3     16.0   10.2
  16.688    9.5     16.688    9.0   17.7    9.0     17.7    2.1     20.     1.99    22.     1.26
  25.0      1.19   158.13     1.19

EIC       1    1.0    1.0   +6
   6.0     21.0      8.0     18.4   10.0   16.0     12.0   14.0     14.0   12.2     16.0   10.2
  16.688    9.5     16.688    9.0   17.7    9.0     17.7   60.0     20.0   57.5     22.0   39.0
  25.0     34.5     91.0     34.5   91.0   37.2    158.13  37.2

GJ        1    1.0    1.0   +6
   6.0     13.2      8.0     12.0   10.0   11.0     12.0   10.0     14.0    9.2     16.0    8.4
  16.688    7.1     16.688    8.0   17.7    8.0     17.7     .79   158.13    .79

XSC       1
   6.0     -.0535           19.5   -.0535     25.2  -.9175       158.13   -.9175
```

CHORD 1
6.0 0.001 19.5 0.0 19.5 3.7 21.4 6.83 91.0 6.83 91.0 7.21
158.13 7.21

XREF 1
6.0 -0.054 19.5 -0.054 19.5 -1.7075 158.13 -1.7075

TWIST 1
6.0 -8.0 17.69 -8.0 19.6 5.7009 158.13 -2.2786

XFA 1
6.0 .3215 158.13 .3215

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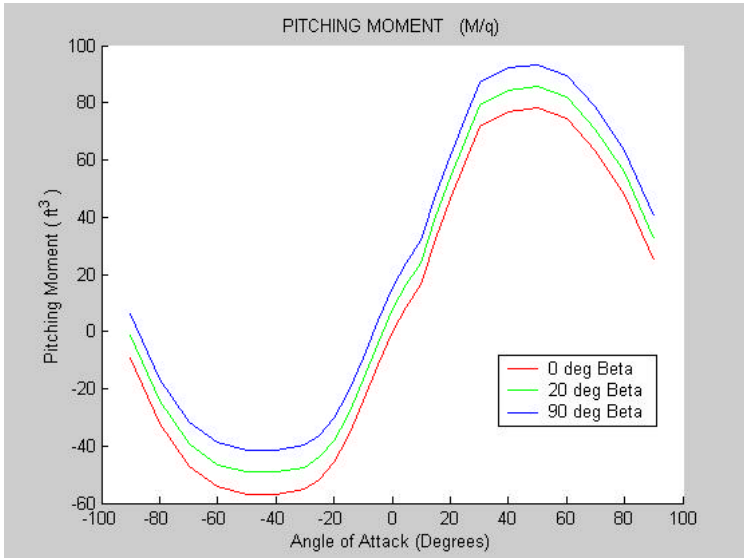
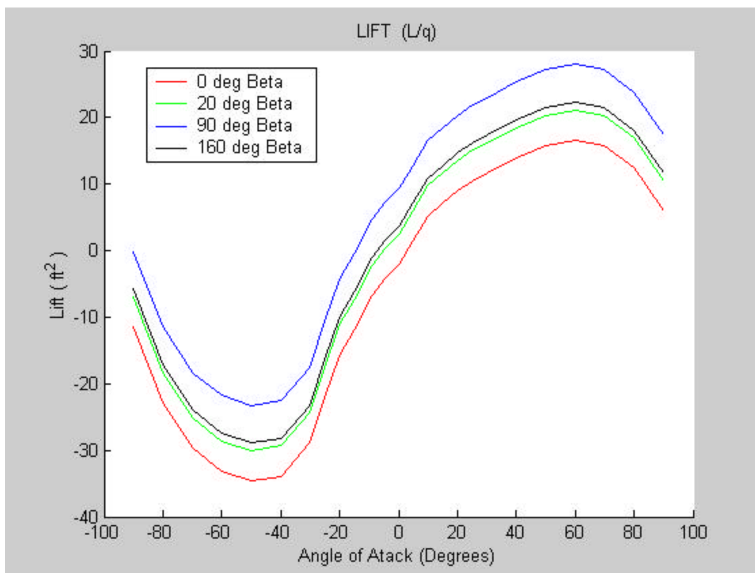
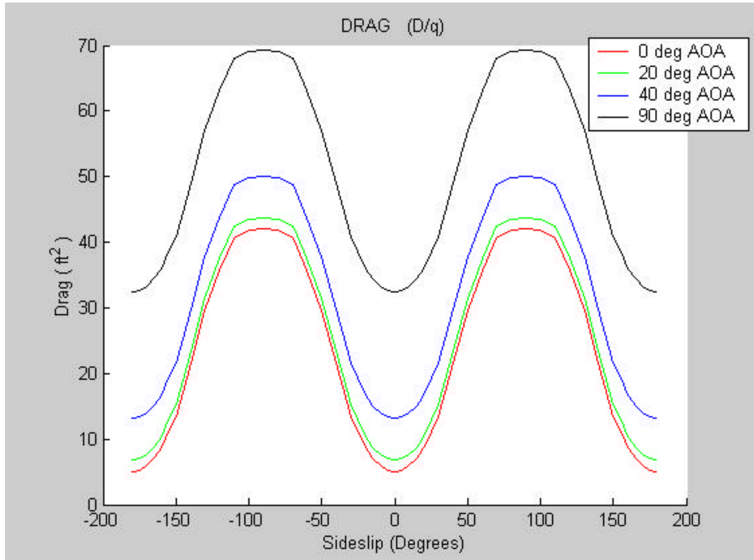
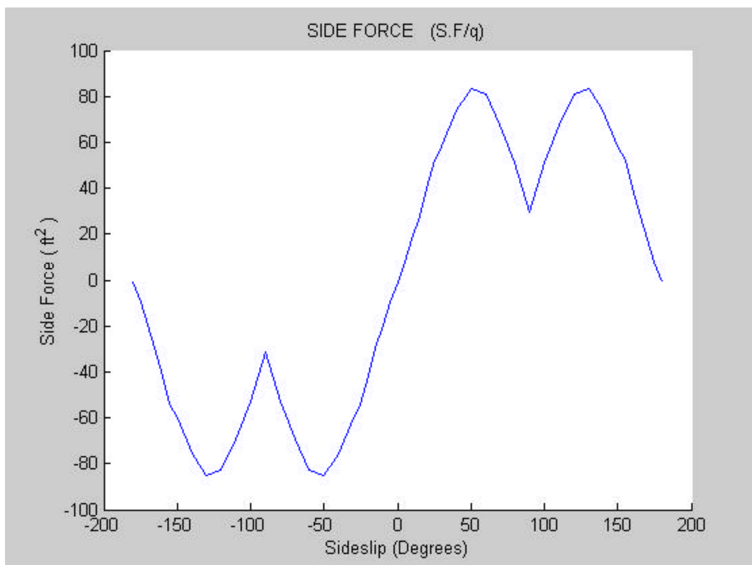
APPENDIX D. FUSELAGE AERODYNAMIC DATA

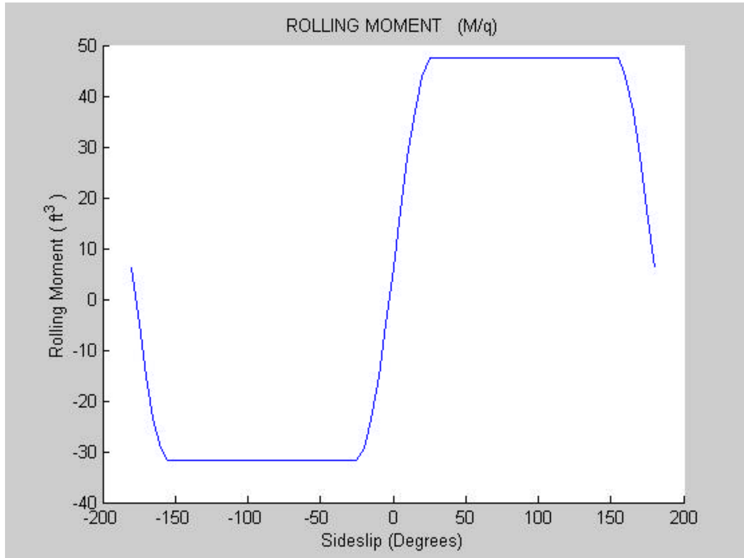
TAIL OFF

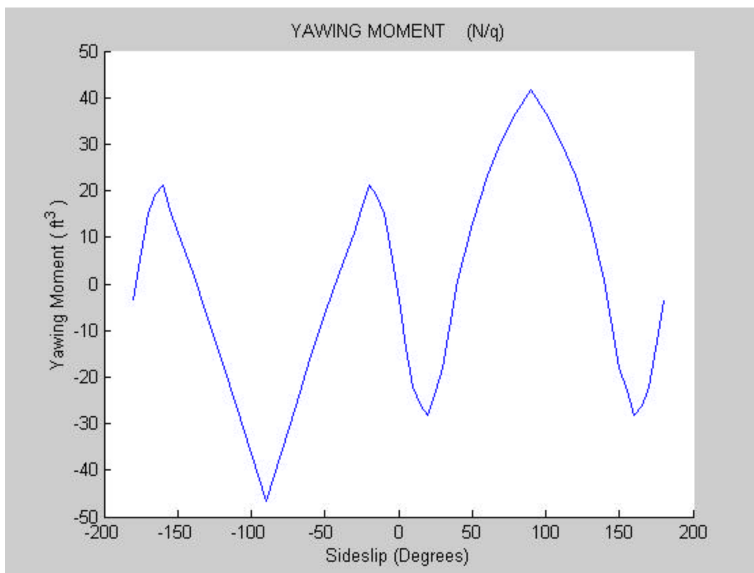




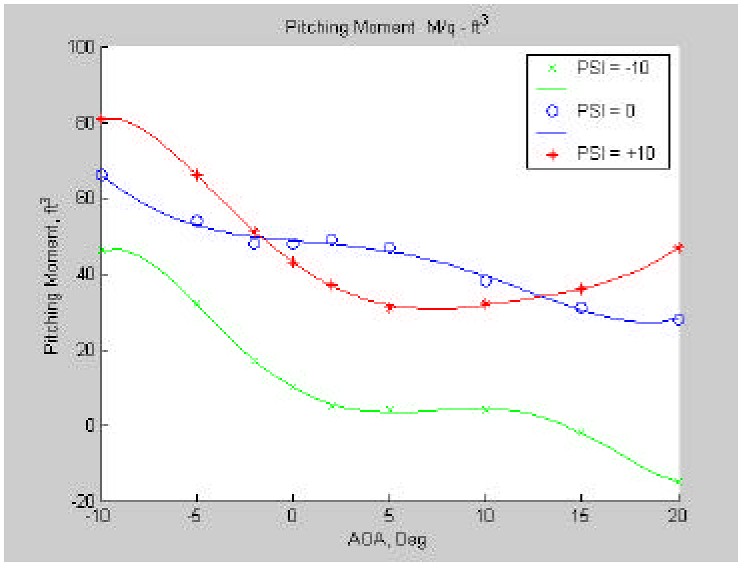

DRAG (D/q)
0 deg AOA
20 deg AOA
40 deg AOA
90 deg AOA
Drag (ft^2)
Sideslip (Degrees)


SIDE FORCE (S.F/q)
Side Force (ft^2)
Sideslip (Degrees)

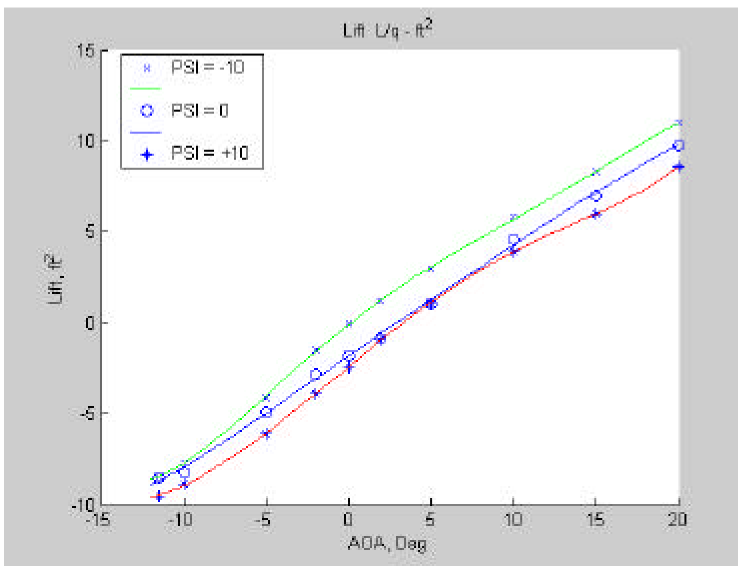

ROLLING MOMENT (M/q)
Rolling Moment (ft^3)
Sideslip (Degrees)
50
40
30
20
10
0
-10
-20
-30
-40
-200
-150
-100
-50
0
50
100
150
200


YAWING MOMENT (N/q)
Yawing Moment (ft^3)
Sideslip (Degrees)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-200
-150
-100
-50
0
50
100
150
200

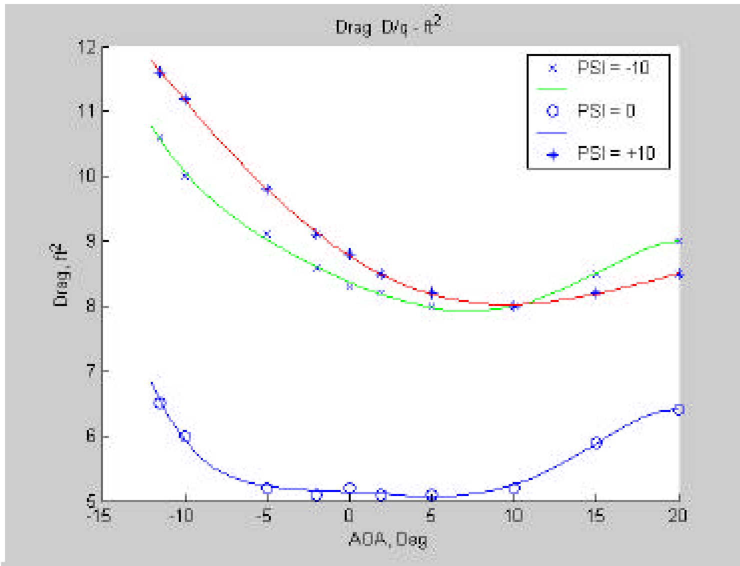
TAIL ON

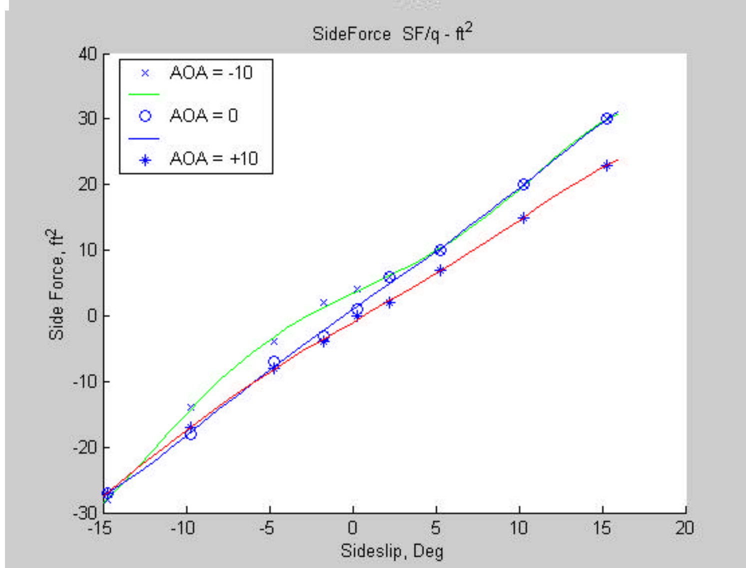


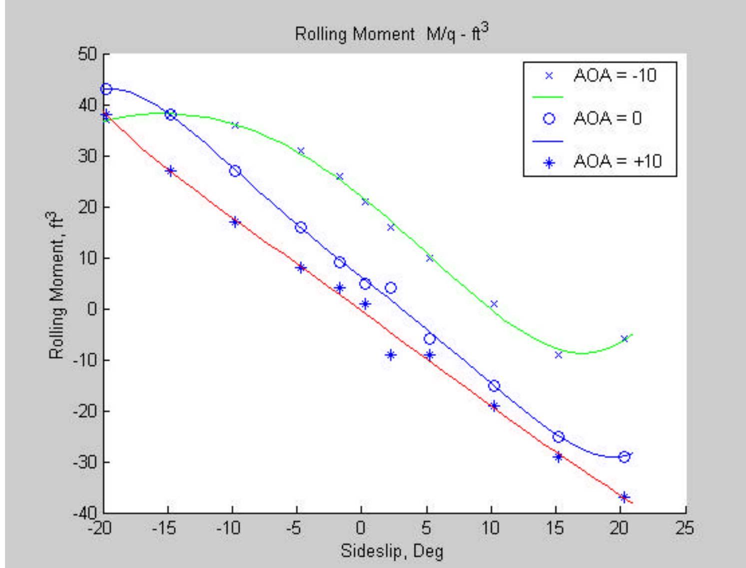
Pitching Moment M/q - ft^3
PSI = -10
PSI = 0
PSI = +10
Pitching Moment, ft^3
AOA, Deg
100
80
60
40
20
0
-20
-10
-5
0
5
10
15
20

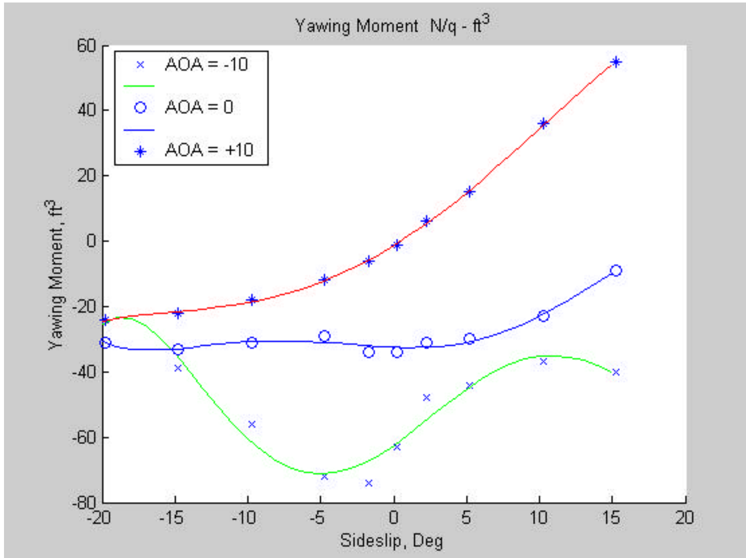


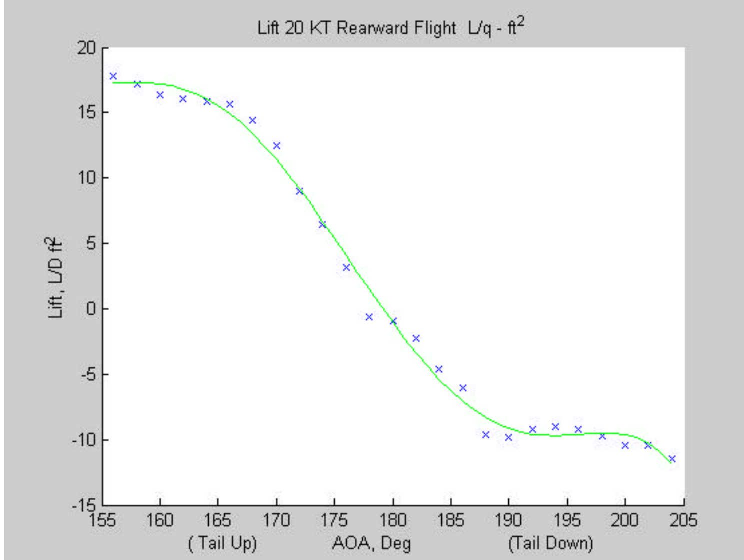
Lift L/q - ft^2
PSI = -10
PSI = 0
PSI = +10
Lift, ft^2
AOA, Deg
15
10
5
0
-5
-10
-15
-10
-5
0
5
10
15
20

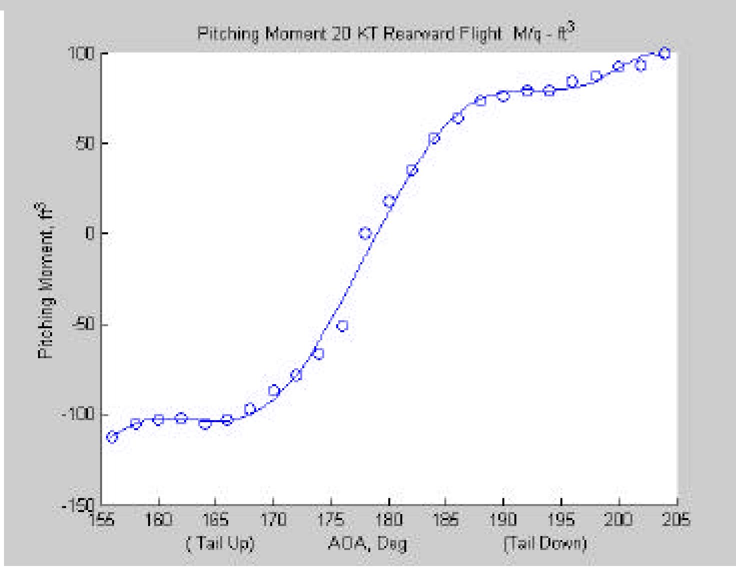

Drag D/q - ft^2
Drag, ft^2
AOA, Deg
PSI = -10
PSI = 0
PSI = +10


SideForce SF/q - ft^2
Side Force, ft^2
Sideslip, Deg
AOA = -10
AOA = 0
AOA = +10

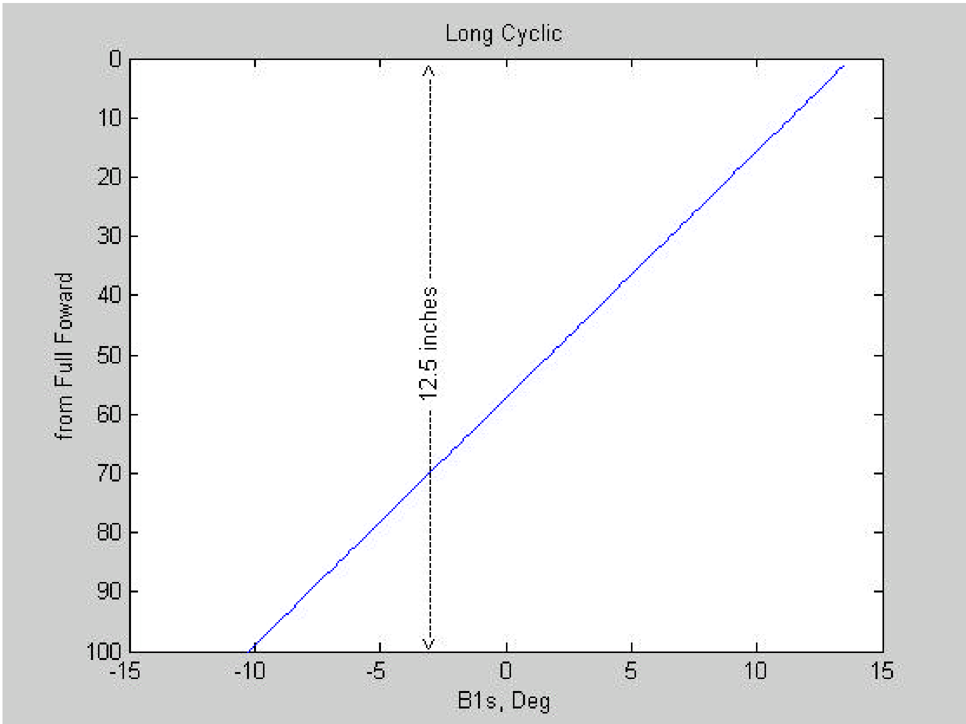

Rolling Moment M/q - ft^3
Rolling Moment, ft^3
Sideslip, Deg
AOA = -10
AOA = 0
AOA = +10

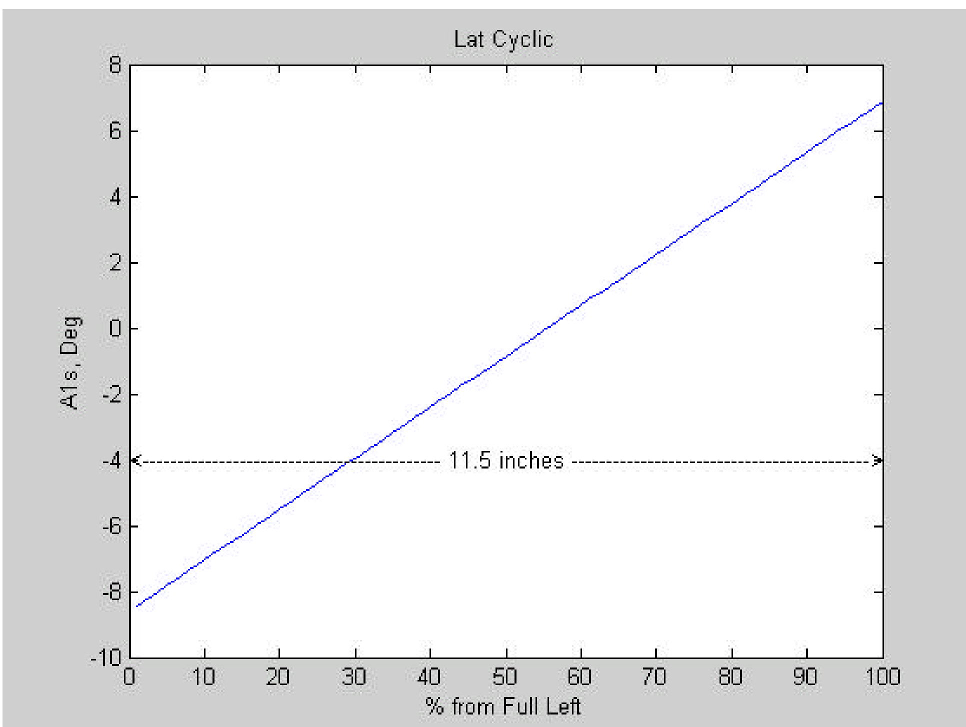

Yawing Moment N/q - ft3
AOA = -10
AOA = 0
AOA = +10
Yawing Moment, ft3
Sideslip, Deg
60
40
20
0
-20
-40
-60
-80
-20
-15
-10
-5
0
5
10
15
20

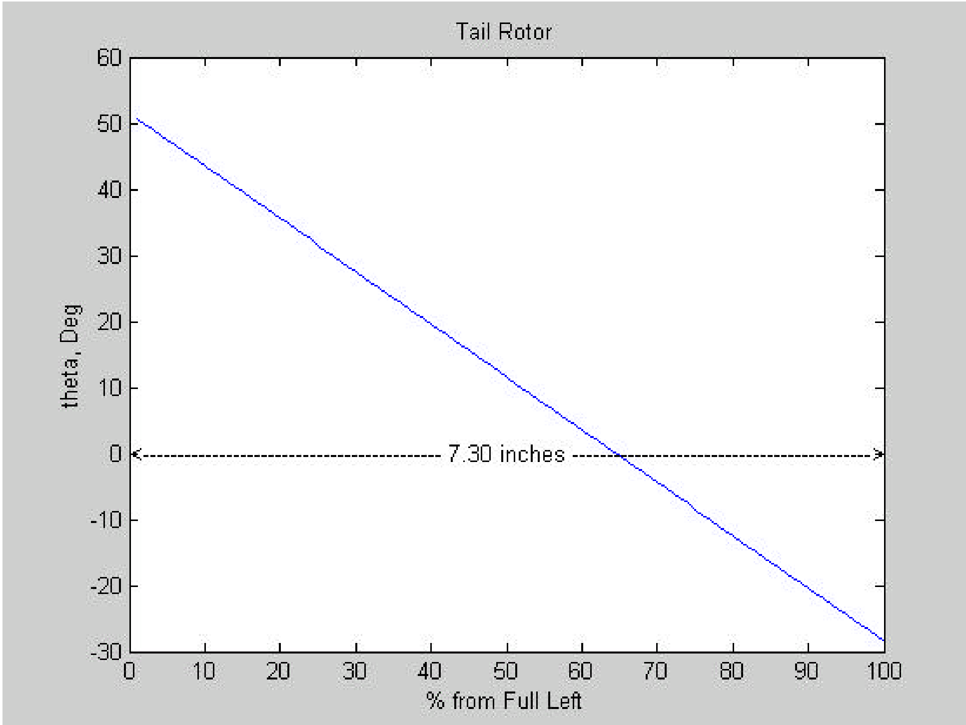

Lift 20 KT Rearward Flight L/q - ft2
Lift, L/D ft2
(Tail Up)
AOA, Deg
(Tail Down)
20
15
10
5
0
-5
-10
-15
155
160
165
170
175
180
185
190
195
200
205


Pitching Moment 20 KT Rearward Flight M/q - ft3
Pitching Moment, ft3
(Tail Up)
AOA, Deg
(Tail Down)
100
50
0
-50
-100
-150
155
160
165
170
175
180
185
190
195
200
205

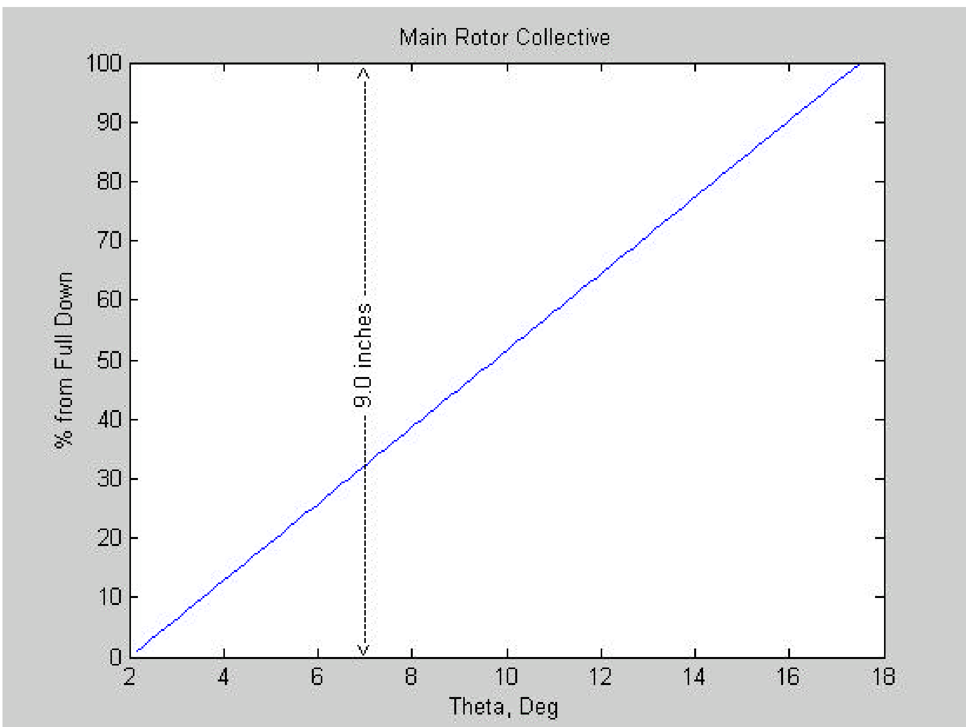
APPENDIX E. FLIGHT CONTROL RIGGING CURVES







Tail Rotor
theta, Deg
% from Full Left
7.30 inches
60
50
40
30
20
10
0
-10
-20
-30
0
10
20
30
40
50
60
70
80
90
100



Main Rotor Collective
% from Full Down
Theta, Deg
9.0 inches
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18

APPENDIX F. FLME MODEL PARAMETERS

MRB (Blade Element)	
Rotor Direction	ccw
Rotor Hub Location	[100.0 0 83.00]
Number of Rotor Blades	4
Blade Tip Loss Factor	0.97
Hub Orientation in Euler Anlges	[0 177 0]
Axis About Which Rotor Shaft Tilts	2
Rotor Nominal Speed	483 rpm
Rotor Radius	157.625 in
Swashplate Phase Angle	-4 deg
Articulated/Rigid Blade/Equal Annulus Area/	
With Lead-lag Dynamics/Linear Lag Damper	
Number of Structural Segments	7
Torque Offset	.375 in
Rotor Precone	0
Precone Offset	0
Flap Hinge Offset	5.5 in
Feathering Hinge Offset	5.5 in
Effective Delta-3 Angle	0
Flap Hinge Spring Stiffness	0
Flap Hinge Damping Coefficient	0
Flap Spring Undeformed Angle	0
Lead-lag Hinge Offset	16.188 in
Linear Lag Damper	
Lag Damper Spring Stiffness	0
Lag Damper Damping Coefficient	500 ft-lb-sec/rad
Lag Spring Undeformed Angle	0
Blade Property Table	bladepropOH-6.tab
Airloads	
Quasi-Steady/Equal Annuli Area	
# of Blade Segments	5
Blade Aerodynamic Root Cutout	20.63 in
Airfoil boundary Nodes	0.0 1.0
Non-Uniform Table	naca0015.tab

Tail Rotor	
Bailey Model	
Rotor Hub Location	[280.18 12 54.26]
Hub Orientation in Euler Angles	[0 0 -90]
Number of Rotor Blades	2
Rotor Radius	2.125 ft
Blade Tip Loss Factor	0.92
Lift Curve Slope	5.73 /deg
Rotor Head Drag Coefficient	0.009
Airfoil Constant Drag Coefficient	0.0087
Airfoil 1st Order Drag Polar Constant	-0.0216
Airfoil 2nd Order Drag Polar Constant	0.4
Blade Pitch Bias	6 deg
Solidity Weighted Blade Chord	4.81 in
Linear Blade Twist	-7
Blade 2nd Moment of Inertia	511 slug ft2
Tangent of Delta Three	1
Partial of Coning wrt Thrust	0.004270 deg/lbf
Initial Collective Pitch Setting	6 deg
Blockage Effect for Low Speed	0.3453
Speed Threshold for Blockage Effect	50 ft/sec
Direction of Rotation Axis	ccw
Rotor Nominal Speed	3018 rpm

Airframe	
Rigid Fuselage	
Interia	
Total Vehical CG	[101.85 0 49.6]
Total Vehical Mass	2200 lbm
Total Roll Moment of Intertia	306 slug ft2
Total Pitch Moment of Inertia	875 slug ft2
Total Yaw Moment of Inertia	689 slug ft2
Total X-Y Product of Interia	0
Total X-Z Product of Intertia	-94.0 slug ft2
Total Y-Z Product of Intertia	0
Empirical Fuselage Airloads	
Airloads Measuring Point	[102.36 0 44.0]
Empirical Airloads	
Reference Area	1.11 ft2
Reference Length	0.333 ft
Non-Uniform Lookup-table	fueselageaeroOH-6.tab

Pilot Station	
Pilot Eye Position	[78 24 44]
Airspeed Sensor Position	[40 0 52]
Airspeed Sensor Orientation	[0 0 0]
Altitude Radar Location	[0 0 0]
Airframe Sensor	
Location	[78 24 44]
Airframe Accelerometer	
Location	[78 -24 44]
Orientation	[0 0 0]
Non-Uniform Table	naca0015.tab
Lifting Surface Property	hstabpropOH-6.tab
Upper Vertical Tail	
Non Controlled Surface	
Lifting Surface Attachment Point	[270 0 54.26]
Lifting Surface Orientation	[0 90 90]
ID for local X-axis direction	1
Lifting Surface Sweep Angle	24 deg
Lifting Surface Surface Span	50 in
Number of Airload Segments	1
Initial Incidence	2.5 deg
Lift Dificiency Factor	1
Non-Uniform Table	naca0015.tab
Lifting Surface Property	vfinpropupOH-6.tab
Lower Vertical Tail	
Non Controlled Surface	
Lifting Surface Attachment Point	[270 0 54.26]
Lifting Surface Orientation	[0 90 90]
ID for local X-axis direction	-1
Lifting Surface Sweep Angle	12.5 deg
Lifting Surface Surface Span	27.36 in
Number of Airload Segments	1
Initial Incidence	0
Lift Dificiency Factor	1
Non-Uniform Table	naca0015.tab
Lifting Surface Property	vfinproplowOH-6.tab

Horizontal Stabilizer	
Non Controlled Surface	
Lifting Surface Attachment Point	[270 0 54.26]
Lifting Surface Orientation	[-90 155 0]
ID for local X-axis direction	-1
Lifting Surface Sweep Angle	0
Lifting Surface Surface Span	67 in
Number of Airload Segments	1
Initial Incidence	0
Lift Dificiency Factor	1
Non-Uniform Table	naca0015.tab
Lifting Surface Property	hstabpropOH-6.tab

Landing Gear	
Left forward Skid	
Location	[78.5 27 14]
Left aft Skid	
Location	[124 26 14]
Right forward Skid	
Location	[78.5 -27 14]
Right aft Skid	
Location	[124 -26 14]
Brake Deflection	0
Max Gear Reaction Load	-9710 lb
Side Friction Coeff	-0.2667 lb sec/ft
Undeflected Strut Length	12.21 in
Zero Force Deflection	2.25 ft
Braking Friction Coeff	0
Rolling Friction Coeff	-0.2667 -0.2667
Damping Coeff	11.42 11.42 lb sec/ft
Stiffness Coeff	14520 22673 lb ft
X-relaxation Factor in Gear Response	0.2
Y-relaxation Factor in Gear Response	0.2
First Stage Maximum Compression	3.25 in
Limits on Y-relaxation	-1.0 1.0
Limits on X-relaxation	-1.0 1.0
Integration Coeff for X-relaxation	0.8
Integration Coeff for Y-relaxation	0.8
Transition Velocity for Friction Coeff	0.2
Weight on Wheel Force	0

##

```
#Lifting surface (vfinproplowOH-6.tab) Property data
#
# X:     {Spanwise station}
# CHORD: {Spanwise  chord distribution}
##
!I X     CHORD
!U nd ft
0.0 1.0
1.0 0.5
```

```
##
#Lifting surface (vfinpropupOH-6.tab) Property data
#
# X:     {Spanwise station}
# CHORD: {Spanwise  chord distribution}
##
!I X     CHORD
!U nd ft
0.0 1.25
1.0 0.594
```

```
##
#Lifting surface (hstabpropOH-6.tab) Property data
#
# X:     {Spanwise station}
# CHORD: {Spanwise  chord distribution}
##
!I X     CHORD
!U nd ft
0.0 1.375
1.0 1.375
```

```
## Template: bladepropOH-6.tab
## Desc:     Rigid Blade Property data for blade element model
#
# BCHORD: Blade chord} {Blade twist} {Chordwise c.g. offset}
# {Blade rotary inertia distribution}
# {Blade flapwise inertia distribution}
# {Blade chordwise inertia distribution}
# {Blade mass distribution}
# {Blade midchord offset from e.a.}
# {Blade tip sweep}   {Blade tip droop}
##
!I BRX BCHORD
!U nd ft
    0.0380    0.0000
    0.1233    0.0000
    0.1234    0.3083
    0.1354    0.5692
    0.5759    0.5692
    0.5760    0.6008
    1.0000    0.6008
!I BRX BTW
!U nd deg
     0.000   -8.000
     0.112   -8.000
     0.125    5.7009
     1.000   -2.2786
!I BRX BCGOFF
!U nd ft
    0.0380   -0.0044
    0.0443   -0.0044
    0.0506   -0.0090
    0.0569   -0.0098
    0.0696   -0.0097
    0.0822   -0.0084
    0.0886   -0.0097
    0.0949   -0.2018
    0.1012   -0.1042
    0.1076   -0.1550
    0.1139   -0.0080
    0.1202   -0.0388
    0.1266   -0.0304
    0.1329   -0.0728
    0.1392   -0.0395
    0.1455   -0.0267
    0.1519   -0.0239
    0.1582   -0.0287
    0.1709   -0.0676
    0.2342   -0.0662
    0.5759   -0.0694
    0.7721   -0.0617
    0.8101   -0.0596
    0.8165   -0.0670
    0.8797   -0.0662
    0.8861   -0.0660
    0.8924   -0.0667
    0.9240   -0.0447
    0.9493   -0.1482
    0.9557   -0.1527
    0.9620   -0.0691
    0.9684   -0.0702
    0.9747   -0.0735
    0.9873   -0.0723
    0.9937   -0.0570
    1.0000   -0.1367
!I BRX  BSEGIXX
!U nd slug-ft
    0.0380   0.0221
    0.0443   0.0031
    0.0506   0.0017
    0.0569   0.0030
    0.0696   0.0032
```

```
    0.0822   0.0032
    0.0886   0.0032
    0.0949   0.0498
    0.1012   0.0532
    0.1076   0.0522
    0.1139   0.0021
    0.1202   0.0024
    0.1266   0.0055
    0.1329   0.0074
    0.1392   0.0044
    0.1455   0.0010
    0.1519   0.0012
    0.1582   0.0014
    0.1709   0.0011
    0.2342   0.0010
    0.5759   0.0011
    0.7721   0.0013
    0.8101   0.0012
    0.8165   0.0013
    0.8797   0.0013
    0.8861   0.0013
    0.8924   0.0013
    0.9240   0.0014
    0.9493   0.0016
    0.9557   0.0017
    0.9620   0.0021
    0.9684   0.0021
    0.9747   0.0019
    0.9873   0.0022
    0.9937   0.0027
    1.0000   0.0002
!I BRX  BSEGIYY
!U nd slug-ft
   0.0380    0.0000
   0.5000    0.0000
   1.0000    0.0000
!I BRX  BSEGIZZ
!U nd slug-ft
   0.0380    0.0000
   0.5000    0.0000
   1.0000    0.0000
!I BRX  BMPL
!U nd slug/ft
    0.0000    0.0000
    0.0380    0.3734
    0.0443    0.1273
    0.0506    0.1300
    0.0570    0.1101
    0.0696    0.1125
    0.0823    0.1498
    0.0886    0.1125
    0.0949    0.5014
    0.1013    0.9918
    0.1076    0.6569
    0.1139    0.1405
    0.1202    0.1601
    0.1266    0.2590
    0.1329    0.2702
    0.1392    0.2957
    0.1456    1.1836
    0.1519    0.0800
    0.1582    0.0669
    0.1709    0.0516
    0.2342    0.0503
    0.5759    0.0507
    0.7722    0.0572
    0.8101    0.0572
    0.8165    0.0594
    0.8797    0.0601
    0.8861    0.0603
    0.8924    0.0596
```

```
    0.9240    0.0668
    0.9494    0.0754
    0.9557    0.0765
    0.9620    0.1578
    0.9684    0.1578
    0.9747    0.1399
    0.9873    0.1645
    0.9937    0.2030
    1.0000    0.0160
!I BRX  BSEGE0
!U nd ft
   0.0380    0.1467
   0.1233    0.1467
   0.1594    0.2187
   1.0000    0.2187
!I BRX  BSWEEP
!U nd deg
   0.0410    0.0
   0.5000    0.0
   1.0000    0.0
!I BRX  BDROOP
!U nd deg
   0.0410    0.0
   0.5000    0.0
   1.0000    0.0
```

```
## Template: fuselageaeroOH6tab
## Desc:     Oh-6 helicopter fuselage airloads table
#
# FAOAARG:  arguments of angle-of-attack [deg]
# FBETAARG: arguments of sideslip angle [deg]
# FCFXTAB:  coef of aerodynamic force along body X-axis [nd]
# FCFYTAB:  coef of aerodynamic force along body Y-axis [nd]
# FCFZTAB:  coef of aerodynamic force along body Z-axis [nd]
# FCMXTAB:  coef of aerodynamic moment about body X-axis [nd]
# FCMYTAB:  coef of aerodynamic moment about body Y-axis [nd]
# FCMZTAB:  coef of aerodynamic moment about body Z-axis [nd]
##

!B FAOAARG 25 1
 -9.0000000000000000e+01  -8.0000000000000000e+01  -7.0000000000000000e+01
 -6.0000000000000000e+01  -5.0000000000000000e+01  -4.0000000000000000e+01
 -3.0000000000000000e+01  -2.5000000000000000e+01  -2.0000000000000000e+01
 -1.5000000000000000e+01  -1.0000000000000000e+01  -5.0000000000000000e+00
  0.0000000000000000e+00   5.0000000000000000e+00   1.0000000000000000e+01
  1.5000000000000000e+01   2.0000000000000000e+01   2.5000000000000000e+01
  3.0000000000000000e+01   4.0000000000000000e+01   5.0000000000000000e+01
  6.0000000000000000e+01   7.0000000000000000e+01   8.0000000000000000e+01
  9.0000000000000000e+01
!B FBETAARG 49 1
 -1.8000000000000000e+02  -1.7500000000000000e+02  -1.7000000000000000e+02
 -1.6500000000000000e+02  -1.6000000000000000e+02  -1.5500000000000000e+02
 -1.5000000000000000e+02  -1.4000000000000000e+02  -1.3000000000000000e+02
 -1.2000000000000000e+02  -1.1000000000000000e+02  -1.0000000000000000e+02
 -9.0000000000000000e+01  -8.0000000000000000e+01  -7.0000000000000000e+01
 -6.0000000000000000e+01  -5.0000000000000000e+01  -4.0000000000000000e+01
 -3.0000000000000000e+01  -2.5000000000000000e+01  -2.0000000000000000e+01
 -1.5000000000000000e+01  -1.0000000000000000e+01  -5.0000000000000000e+00
  0.0000000000000000e+00   5.0000000000000000e+00   1.0000000000000000e+01
  1.5000000000000000e+01   2.0000000000000000e+01   2.5000000000000000e+01
  3.0000000000000000e+01   4.0000000000000000e+01   5.0000000000000000e+01
  6.0000000000000000e+01   7.0000000000000000e+01   8.0000000000000000e+01
  9.0000000000000000e+01   1.0000000000000000e+02   1.1000000000000000e+02
  1.2000000000000000e+02   1.3000000000000000e+02   1.4000000000000000e+02
  1.5000000000000000e+02   1.5500000000000000e+02   1.6000000000000000e+02
  1.6500000000000000e+02   1.7000000000000000e+02   1.7500000000000000e+02
  1.8000000000000000e+02
!B FCFXTAB 25 49
  1.1482781639119400e+01   2.7960413122563715e+01   3.7663427621893000e+01
  4.0563805726897037e+01   3.8198831779873103e+01   3.2701028881105678e+01
  2.4033089299876586e+01   1.7785829639145106e+01   1.2788938777911406e+01
  9.6050028430740788e+00   7.1439603390540878e+00   5.7764644268371041e+00
  5.0999999999999996e+00   5.2037921925245358e+00   6.2418734972799275e+00
  7.5794118515892039e+00   9.5167430705951936e+00   1.1811072262964048e+01
  1.4271237525588257e+01   1.9061124828453959e+01   2.4358491402594847e+01
  2.6691891050943646e+01   2.4711130049292052e+01   1.7670616889255943e+01
  5.9652000637470772e+00   1.0724173738994770e+01   2.7378996063143095e+01
  3.7280526871771087e+01   4.0398250929190553e+01   3.8263215258545806e+01
  3.2994043582525578e+01   2.4546943969549226e+01   1.8405898512503434e+01
  1.3509827706498404e+01   1.0420590382316602e+01   8.0469393284965420e+00
  6.7590709488430596e+00   6.1539640551233825e+00   6.3198626312073296e+00
  7.4103567710950218e+00   8.7907046808177736e+00   1.0760339999708751e+01
  1.3076446790627093e+01   1.5547976683024263e+01   2.0332539434039294e+01
  2.5583013480951315e+01   2.7838637619926523e+01   2.5753664298076821e+01
  1.8583365712913416e+01   6.7238079638717059e+00   1.0344869788932456e+01
  2.7497296449525685e+01   3.7903787463302407e+01   4.1529065699605852e+01
  3.9889853497318676e+01   3.5069023386405085e+01   2.7010545212149982e+01
  2.1040121233835240e+01   1.6292603868833453e+01   1.3328841078219870e+01
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1.4919080647207476e+01	1.7042858110546362e+01	1.7731024073346312e+01
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0.3393	0.3567	0.4782	0.7305	0.8566	1.0510	1.2576	1.3897
0.3927	0.4066	0.4908	0.7041	0.8226	1.0173	1.2242	1.3608
0.4463	0.4575	0.5247	0.6990	0.8089	0.9954	1.1965	1.3325
0.5001	0.5087	0.5616	0.7097	0.8063	0.9837	1.1771	1.3077
0.5539	0.5611	0.6045	0.7298	0.8189	0.9827	1.1647	1.2767
0.6078	0.6148	0.6528	0.7593	0.8408	0.9910	1.1611	1.1981
0.6617	0.6685	0.7015	0.7961	0.8668	1.0078	1.1563	1.1538
0.7156	0.7224	0.7511	0.8353	0.9023	1.0317	1.1322	1.1380
0.7700	0.7771	0.8055	0.8838	0.9406	1.0591	1.1268	1.1374
0.8277	0.8382	0.8788	0.9473	0.9912	1.0810	1.1397	1.1519
0.8550	0.8550	0.9300	0.9600	1.0100	1.0700	1.1000	1.1200
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   0.1230    0.0281    0.0233    0.0200    0.0186    0.0161    0.0136    0.0123
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   0.0277    0.0233    0.0191    0.0164    0.0152    0.0133    0.0113    0.0103
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-0.0800	-0.1100	-0.1300
-0.0800	-0.1250	-0.1400
-0.1000	-0.2000	-0.1650
-0.2250	-0.1500	-0.1550
-0.3400	-0.2500	-0.2650
-0.3500	-0.2500	-0.0500
-0.4000	-0.2100	-0.2700
-0.4600	-0.3200	-0.1500
-0.1500	-0.1500	-0.4100
-0.4800	-0.4000	-0.3000
-0.2600	-0.4250	-0.2100
-0.4600	-0.2250	-0.3800
-0.5000	-0.3150	-0.4200
-0.2800	-0.2300	-0.4150
-0.4500	-0.3400	-0.4500
-0.2750	-0.4250	-0.4500
-0.4900	-0.5400	-0.1900
-0.5400	-0.3600	-0.3900
-0.5600	-0.5800	-0.5400
-0.4700	-0.4800	-0.4900
-0.4100	-0.4000	-0.4400
-0.4200	-0.4300	-0.5250
-0.4000	-0.4150	-0.4750
-0.5000	-0.4200	-0.3800
-0.3500	-0.4000	-0.3800
-0.3250	-0.3200	-0.3300
-0.2850	-0.3000	-0.3000
-0.2750	-0.2900	-0.3500
-0.4200	-0.4600	-0.4250
-0.2800	-0.2800	-0.3100
0.0250	0.0800	-0.0600

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APPENDIX G. ADDITIONAL SCRIPTS

OGE HOVER PERFORMANCE

```
wtswp = [0.5:0.25:1.5];
//Set trim target torlerance
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VXBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VyBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VzBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_PD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_qD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_rD   = 0.001;
group myresults
  //Height above ground
  zor = 3.64;
  WORLD_MODEL_AIRFRAME_CPG_TESTCOND_POSZIC ..
                    = -zor * WORLD_MODEL_ROTOR1_ROTOR_DATA_RMR;
  wind1 = 0;   wind2 = 2.5;
  ny = 2;
  wt = WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT;
  wt = wt*world_wtswp';
  nx = prod(size(wtswp));
  ct = zeros(nx,ny);
  cp23 = zeros(nx,ny);
  for iy = 1:ny
    //Wind magnitude
    WORLD_MODEL_CPG_TESTCOND_WINMAGH = wind$iy;
    exec("xatestcond.exc",1);
    for ix = 1:nx
      WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT = wtswp(ix);
      exec("xaconfig.exc",1);
      exec("xamodeltrim.exc",1);
      ct(ix,iy)= world_analysis_trimtest_results_trimout(14);
      cp23(ix,iy)= world_analysis_trimtest_results_trimout(16)^(2/3);
    end
  end
  //Save results
  save("figure-5.sav",wind1,wind2,zor,ct,cp23);
parentg
//Plot
exec("figure-5.plt",1);
//EOF
```

IGE HOVER PERFORMANCE

```
wtswp = [0.5:0.25:1.5];
//Set trim target torlerance
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VXBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VyBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VzBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_PD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_qD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_rD   = 0.001;
group myresults
  //Height above ground
  zor = 3.64;
  WORLD_MODEL_AIRFRAME_CPG_TESTCOND_POSZIC ..
                       = -zor * WORLD_MODEL_ROTOR1_ROTOR_DATA_RMR;
  wind1 = 0; wind2 = 2.5;
  ny = 2;
  wt = WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT;
  wt = wt*world_wtswp';
  nx = prod(size(wtswp));
  ct = zeros(nx,ny);
  cp23 = zeros(nx,ny);
  for iy = 1:ny
    //Wind magnitude
    WORLD_MODEL_CPG_TESTCOND_WINMAGH = wind$iy;
    exec("xatestcond.exc",1);
    for ix = 1:nx
      WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT = wtswp(ix);
      exec("xaconfig.exc",1);
      exec("xamodeltrim.exc",1);
      ct(ix,iy)= world_analysis_trimtest_results_trimout(14);
      cp23(ix,iy)= world_analysis_trimtest_results_trimout(16)^(2/3);
    end
  end
  //Save results
  save("figure-5.sav",wind1,wind2,zor,ct,cp23);
parentg
//Plot
exec("figure-5.plt",1);
//EOF
```

LONGITUDINAL CONTROL MOTION

```
exec("xafltestpar_init.exc",1);
```

```
group myresults
  WT = 2000;
  //Autorotation
  WORLD_ANALYSIS_XAFLTEST_AUTOROT_TESTCOND_WT = WT;
  pushg( WORLD_ANALYSIS_XAFLTEST_AUTOROT_IN )
    ISWTSWP = 0;  ISHPSWP = 0;  FWDSPDSWP = [40 100 10];
  popg,  exec("xaftautorot.exc",1);
  pushg( WORLD_ANALYSIS_XAFLTEST_AUTOROT_RESULTS_PLOTCTRL )
    ISFWDSPDSWP = 1;  ISWTSWP = 0;  ISHPSWP = 0;
    WTSWP = 2000;  HPSWP = 0;
  popg,  exec("xaftautorotplotmap.exc",1);
  speed1 = WORLD_ANALYSIS_XAFLTEST_AUTOROT_RESULTS_XY4PLOT_VEQ;
  xbtot1 = WORLD_ANALYSIS_XAFLTEST_AUTOROT_RESULTS_XY4PLOT_XBTRMPC;
  //Level flight
  WORLD_ANALYSIS_XAFLTEST_FWDSPD_TESTCOND_WT = WT;
  pushg( WORLD_ANALYSIS_XAFLTEST_FWDSPD_IN )
    ISWTSWP = 0;  ISHPSWP = 0;  FWDSPDSWP = [-20 140 10];
  popg,  exec("xaftfwdspd.exc",1);
  pushg( WORLD_ANALYSIS_XAFLTEST_FWDSPD_RESULTS_PLOTCTRL )
    ISFWDSPDSWP = 1;  ISWTSWP = 0;  ISHPSWP = 0;
    WTSWP = 2000;  HPSWP = 0;
  popg,  exec("xaftfwdspdplotmap.exc",1);
  speed2 = WORLD_ANALYSIS_XAFLTEST_FWDSPD_RESULTS_XY4PLOT_VEQ;
  xbtot2 = WORLD_ANALYSIS_XAFLTEST_FWDSPD_RESULTS_XY4PLOT_XBTRMPC;
  //Save results
  save("figure-23.sav");
  //Plot
  exec("figure-23.plt",1);
//EOF//
```

SIDEWARD FLIGHT

```
group myresults
  //Hover
  WT0   = 1956.5;
  BLCG0 = -0.93;
  WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT = WT0;
  WORLD_MODEL_CPG_CONFIGPAR_BLCG = BLCG0/12;
  exec("xaconfig.exc",1);
  exec("xamodeltrim.exc",1);
  VEQ0  = 0;
```

```
XATRM0= WORLD_ANALYSIS_TRIMTEST_RESULTS_TRIMOUT(83);
XPTRM0= WORLD_ANALYSIS_TRIMTEST_RESULTS_TRIMOUT(85);
XBTRM0= WORLD_ANALYSIS_TRIMTEST_RESULTS_TRIMOUT(82);
//Left sideward flight
exec("xafltestpar_init.exc",1);
WT1   = 2036.5;
BLCG1 = -2.98;
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTCOND_WT   = WT1;
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTCOND_BLCG = BLCG1;
pushg(WORLD_ANALYSIS_XAFLTEST_LOWSPD_IN)
  ISWTSWP = 0;  ISHPSWP = 0;
  LNGSPDSWPFORMAT = 1;  LNGSPDSWP = 0;
  LATSPDSWP = [-20 -5 5];
popg,  exec("xaftlowspd.exc",1);
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTID = 2;
pushg( WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_PLOTCTRL )
  ISLWSPDSWP = 1;  ISWTSWP=0;  ISHPSWP=0;  ISWHLHSWP=0;
  WTSWP = 2036.5; HPSWP=0;  WHLHSWP=999;
popg,  exec("xaftlowspdplotmap.exc",1);
VEQ1  = WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_VEQ;
XATRM1= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XATRMPC;
XPTRM1= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XPTRMPC;
XBTRM1= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XBTRMPC;
//Right sideward flight
exec("xafltestpar_init.exc",1);
WT2   = 2036.5;
BLCG2 = 3;
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTCOND_WT   = WT2;
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTCOND_BLCG = BLCG2;
pushg(WORLD_ANALYSIS_XAFLTEST_LOWSPD_IN)
  ISWTSWP = 0;  ISHPSWP = 0;
  LNGSPDSWPFORMAT = 1;  LNGSPDSWP = 0;
  LATSPDSWP = [3 12 3];
popg,  exec("xaftlowspd.exc",1);
WORLD_ANALYSIS_XAFLTEST_LOWSPD_TESTID = 2;
pushg( WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_PLOTCTRL )
  ISLWSPDSWP = 1;  ISWTSWP=0;  ISHPSWP=0;  ISWHLHSWP=0;
  WTSWP = 2036.5; HPSWP=0;  WHLHSWP=999;
popg,  exec("xaftlowspdplotmap.exc",1);
VEQ2  = WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_VEQ;
XATRM2= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XATRMPC;
XPTRM2= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XPTRMPC;
XBTRM2= WORLD_ANALYSIS_XAFLTEST_LOWSPD_TEST2_RESULTS_XY4PLOT_XBTRMPC;
```

```
  VEQ = [VEQ1; VEQ0; VEQ2];
  XATRM = [XATRM1; XATRM0; XATRM2];
  XPTRM = [XPTRM1; XPTRM0; XPTRM2];
  XBTRM = [XBTRM1; XBTRM0; XBTRM2];
  //Save results
  save("figure-30.sav");
  //Plot
  exec("figure-30.plt",1);
//EOF//
```

STATIC LONGITUDINAL STABILITY

```
exec("xafltestpar_init.exc",1);
group myresults
//First Plot
  HPres = 1500;
  WT1 = 2011;
  FSCG1 = 97.2;
  WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_HP   = HPres;
  WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_WT   = WT1;
  WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_FSCG = FSCG1;
  pushg(WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_IN)
    ISFSCGSWP=0;
    ISSPDSWP=1;     SPDSWPFORMAT=1;     SPDSWP=[40 80 110];
    ISSPDPRTRBSWP=1; SPDPRTRBSWPFORMAT=0; SPDPRTRBSWP=[ -20 25 5];
  popg,  exec("xaftlngstatstab.exc",1);
  pushg(WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT)
    ISCOMPARE = 0;  ISMULTIPLE = 0;  sweepindx1 = 2;
  popg,  exec("xaftlngstatstabstdplt.exc",1);
  vtrim1 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_pltpar;
  xbtrm1 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_ynom1(1,:)';
  speed1 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_x4plot1;
  xbtot1 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_y4plot1;
  [nn junk] = size(speed1);
  speed1 = speed1 + ones(nn,1)*vtrim1';
  //Second plot
  HPres = 1500;
  WT2 = 2693;
  FSCG2 = 103.7;
  WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_HP   = HPres;
  WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_WT   = WT2;
```

```
 WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_TESTCOND_FSCG = FSCG2;
 pushg(WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_IN)
   ISFSCGSWP=0;
   ISSPDSWP=1;    SPDSWPFORMAT=1;    SP DSWP=[40 80 110];
   ISSPDPRTRBSWP=1; SPDPRTRBSWPFORMAT=0; SPDPRTRBSWP=[ -20 25 5];
 popg,  exec("xaftlngstatstab.exc",1);
 pushg(WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT)
   clear;
   ISCOMPARE = 0;  ISMULTIPLE = 0;  sweepindx1 = 2;
 popg,  exec("xaftlngstatstabstdplt.exc",1);
 vtrim2 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_pltpar;
 xbtrm2 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_ynom1(1,:)';
 speed2 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_x4plot1;
 xbtot2 = WORLD_ANALYSIS_XAFLTEST_LNGSTATSTAB_RESULTS_STDPLOT_y4plot1;
 [nn junk] = size(speed2);
 speed2 = speed2 + ones(nn,1)*vtrim2';
 clear(nn,junk);
 //Save results
 save("figure-22.sav");
 //Plot
 exec("figure-22.plt",1);
//EOF//
```

DYNAMIC RESPONSE TO LONGITUDINAL CONTROL INPUT

```
// VWEIGHT {Gross weight [lbf]}    {2017} world_myresults
// FSCG   {C.G. position [in]}    {97.2} world_myresults
// VEQ    {Airspeed [knots]}     {100} world_myresults
// HPRES  {Pressure altitude [ft]}  {1200} world_myresults
// XBamp  {Lng control amplitude [%]} {12} world_myresults
// XAamp  {Lat control amplitude [%]}  {4} world_myresults
exec("xamodeltrim.exc",1);
goto world;
group myresults
 if( exists(VWEIGHT)==0 )
   VWEIGHT = 2017;
   FSCG  = 97.2;
   VEQ   = 100;
   HPRES = 1200;
   XBamp = 12;
   XAamp = 4;
```

```
end
//Set configuration and test condition
WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT     = VWEIGHT;
WORLD_MODEL_CPG_CONFIGPAR_FSCG        = FSCG/12;
WORLD_MODEL_CPG_TESTCOND_HPRES        = HPRES;
//Trim
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VXBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VyBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VzBD = 0.004;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_PD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_qD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_rD   = 0.001;
for iv=1:5
  WORLD_MODEL_AIRFRAME_CPG_TESTCOND_VEQ = (VEQ/5)*iv;
  exec("xatestcond.exc",1);
  exec("xaconfig.exc",1);
  exec("xamodeltrim.exc",1);
end
clear(ANS,DUMMY,ISGAMHTRIM,ISGAMVTRIM,ISKVEQTRIM,TOTALVEQ);
//Input
varlist @extinputs = [];
varlist @extinputs + WORLD_MODEL_CONTROL_CPG_IN_XB, ..
                WORLD_MODEL_CONTROL_CPG_IN_XA;
WORLD_ANALYSIS_NONLINEARRESP_in_UEXT = [];
//Step Input Profile foo XB
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_amp      = xbamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_stime    = 0.25;//Start time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_rtime    = 0.1; //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_steptime = 1;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_ftime    = 0.1; //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_tottime  = 3;   //Total time
exec("xastep.exc",1);
//Step Input Profile foo XA
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_amp      = xaamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_stime    = 0.25;//Start time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_rtime    = 0.1; //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_steptime = 1;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_ftime    = 0.1; //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_tottime  = 3;   //Total time
exec("xastep.exc",1);
//Outputs
varlist @genoutputs = [];
varlist @genoutputs + WORLD_MODEL_AIRFRAME_CPG_XAOUT_THETAd, ..
```

```
            WORLD_MODEL_AIRFRAME_CPG_XAOUT_THETA, ..
            WORLD_MODEL_AIRFRAME_CPG_XAOUT_AZB, ..
            WORLD_MODEL_AIRFRAME_CPG_XAOUT_PHI;
  //Time response
  exec("xanonlinear.exc",1);
  uext = WORLD_ANALYSIS_NONLINEARRESP_in_UEXT;
  ynl  = world_analysis_nonlinearresp_results_ynl;
  time = world_analysis_nonlinearresp_results_time;
  //Results
  XBTOT  = 100 - (WORLD_MODEL_CONTROL_DATA_XBTRM + uext(:,1));
  THETAd = ynl(:,1) * world_data_r2d;
  THETA  = ynl(:,2) * world_data_r2d;
  AZB    = -ynl(:,3) / world_data_gravity(3) + 1;
  XATOT  = WORLD_MODEL_CONTROL_DATA_XATRM + uext(:,2);
  PHI    = -ynl(:,4) * world_data_r2d;
  //Save Results
  save("figure-24.sav");
parentg
//Plot
exec("figure-24.plt",1);
//EOF//
```

STATIC LATERAL / DIRCTIONAL STABILITY

```
WORLD_MODEL_AIRFRAME_FSBOOM_LEN(3) = 0.05;
exec("xafltestpar_init.exc",1);
group myresults
  //Test conditions
  WT    = 1993;
  FSCG  = 100.7;
  HPres = 550;
  speed = [35 70 100];
  WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_TESTCOND_WT   = WT;
  WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_TESTCOND_FSCG = FSCG;
  WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_TESTCOND_HP   = HPres;
  pushg(WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_IN)
    ISBETASWP=1;  BETASWPFORMAT=0;  BETASWP=[-20 20 5];
    ISSPDSWP=1;   SPDSWPFORMAT=1;   SPDSWP=[35 70 100];
  popg,  exec("xaftlatstatstab.exc",1);
  pushg( WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_RESULTS_PLOTCTRL )
```

```
    ISBETASWP = 1;  ISSPDSWP = 0;  SPDSWP = [35 70 100];
  popg,  exec("xaftlatstatstabplotmap.exc",1);
  GAMH = WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_RESULTS_XY4PLOT_DELTAGAMH;
  PHI = WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_RESULTS_XY4PLOT_PHI;
  XPTRM = WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_RESULTS_XY4PLOT_XPTRMPC;
  XATRM = WORLD_ANALYSIS_XAFLTEST_LATSTATSTAB_RESULTS_XY4PLOT_XATRMPC;
  //Save results
  save("figure-26.sav");
  //Plot
  exec("figure-26.plt",1);
//EOF//
```

MANEUVERING STABILITY

```
// VWEIGHT {Gross weight [lbf]}      {2017} world_myresults
// FSCG    {C.G. position [in]}      {97.2} world_myresults
// VEQ     {Airspeed [knots]}        {70} world_myresults
// HPRES   {Pressure altitude [ft]}  {1200} world_myresults
// XBamp   {Lng control amplitude [%]} {7} world_myresults
// XAamp   {Lat control amplitude [%]}  {2} world_myresults
//End-userscr-variable
exec("xamodeltrim.exc",1);
goto world;
group myresults
  if( exists(VWEIGHT)==0 )
    VWEIGHT = 2017;
    FSCG  = 97.2;
    VEQ   = 70;
    HPRES = 1200;
    XBamp = 7;
    XAamp = 2;
  end
  //Set configuration and test condition
  WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT     = VWEIGHT;
  WORLD_MODEL_CPG_CONFIGPAR_FSCG        = FSCG/12;
  WORLD_MODEL_CPG_TESTCOND_HPRES        = HPRES;
  //Trim
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VXBD = 0.004;
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VyBD = 0.004;
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VzBD = 0.004;
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_PD   = 0.001;
```

```
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_qD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_rD   = 0.001;
for iv=1:7
  WORLD_MODEL_AIRFRAME_CPG_TESTCOND_VEQ = (VEQ/7)*iv;
  exec("xatestcond.exc",1);
  exec("xaconfig.exc",1);
  exec("xamodeltrim.exc",1);
end
clear(ANS,DUMMY,ISGAMHTRIM,ISGAMVTRIM,ISKVEQTRIM,TOTALVEQ);
//Input
varlist @extinputs = [];
varlist @extinputs + WORLD_MODEL_CONTROL_CPG_IN_XB, ..
                WORLD_MODEL_CONTROL_CPG_IN_XA;
WORLD_ANALYSIS_NONLINEARRESP_in_UEXT = [];
//Step Input Profile foo XB
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_amp      = xbamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_stime    = 0.6;//Start time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_rtime    = 0.07; //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_steptime = 2.25;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_ftime    = 0.5; //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_tottime  = 5;   //Total time
exec("xastep.exc",1);
//Step Input Profile foo XA
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_amp      = xaamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_stime    = 0.6;//Start time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_rtime    = 0.05; //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_steptime = 0.15;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_ftime    = 0.05; //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_tottime  = 5;   //Total time
exec("xastep.exc",1);
//Outputs
varlist @genoutputs = [];
varlist @genoutputs + WORLD_MODEL_AIRFRAME_CPG_XAOUT_THETAd, ..
                WORLD_MODEL_AIRFRAME_CPG_XAOUT_THETA, ..
                WORLD_MODEL_AIRFRAME_CPG_XAOUT_AZB, ..
                WORLD_MODEL_AIRFRAME_CPG_XAOUT_PHI, ..
                                WORLD_MODEL_AIRFRAME_CPG_XAOUT_PSI;
//Time response
exec("xanonlinear.exc",1);
uext = WORLD_ANALYSIS_NONLINEARRESP_in_UEXT;
ynl  = world_analysis_nonlinearresp_results_ynl;
time = world_analysis_nonlinearresp_results_time;
//Results
```

```
  XBTOT  = 100 - (WORLD_MODEL_CONTROL_DATA_XBTRM + uext(:,1));
  THETAd = ynl(:,1) * world_data_r2d;
  THETA  = ynl(:,2) * world_data_r2d;
  AZB    = -ynl(:,3) / world_data_gravity(3) + 1;
  XATOT  = WORLD_MODEL_CONTROL_DATA_XATRM + uext(:,2);
  PHI    = -ynl(:,4) * world_data_r2d;
  PSI   =  ynl(:,5);
  //Save Results
  save("figure-25.sav");
parentg
//Plot
exec("figure-25.plt",1);
//EOF//
```

DYNAMIC RESPONSE TO DIRECTIONAL PULSE INPUT

```
// VWEIGHT {Gross weight [lbf]}      {2017} world_myresults
// FSCG    {C.G. position [in]}      {97.2} world_myresults
// VEQ     {Airspeed [knots]}        {50} world_myresults
// HPRES   {Pressure altitude [ft]}  {1200} world_myresults
// XBamp   {Lng control amplitude [%]} {4} world_myresults
// XAamp   {Lat control amplitude [%]}  {-1.5} world_myresults
exec("xamodeltrim.exc",1);
goto world;
group myresults
  if( exists(VWEIGHT)==0 )
    VWEIGHT = 2017;
    FSCG  = 97.2;
    VEQ   = 50;
    HPRES = 1200;
    XPamp = 4;
    XAamp = -1.5;
  end
  //Set configuration and test condition
  WORLD_MODEL_CPG_CONFIGPAR_VWEIGHT     = VWEIGHT;
  WORLD_MODEL_CPG_CONFIGPAR_FSCG        = FSCG/12;
  WORLD_MODEL_CPG_TESTCOND_HPRES        = HPRES;
  //Trim
  WORLD_ANALYSIS_TRIMTEST_T RIMTOL_VXBD = 0.004;
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VyBD = 0.004;
  WORLD_ANALYSIS_TRIMTEST_TRIMTOL_VzBD = 0.004;
```

```
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_PD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_qD   = 0.001;
WORLD_ANALYSIS_TRIMTEST_TRIMTOL_rD   = 0.001;
for iv=1:10
  WORLD_MODEL_AIRFRAME_CPG_TESTCOND_VEQ = (VEQ/10)*iv;
  exec("xatestcond.exc",1);
  exec("xaconfig.exc",1);
  exec("xamodeltrim.exc",1);
end
clear(ANS,DUMMY,ISGAMHTRIM,ISGAMVTRIM,ISKVEQTRIM,TOTALVEQ);
//Input
varlist @extinputs = [];
varlist @extinputs + WORLD_MODEL_CONTROL_CPG_IN_XP, ..
                 WORLD_MODEL_CONTROL_CPG_IN_XA;
WORLD_ANALYSIS_NONLINEARRESP_in_UEXT = [];
//Step Input Profile foo XB
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_amp      = xpamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_stime    = 0.25;//Start time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_rtime    = 0.1; //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_steptime = 1;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_ftime    = 0.1; //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_stepgrp_tottime  = 9;   //Total time
exec("xastep.exc",1);
//Step Input Profile foo XA
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_amp      = xaamp; //Amplitude
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_stime    = 0.25;  //Start time
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_rtime    = 1.75;   //Rise time
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_steptime = 4.0;   //Step time
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_ftime    = 2.0;   //Fall time
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_tottime  = 9;     //Total time
WORLD_ANALYSIS_NONLINEARRESP_in_doubletgrp_delaytime = 0.0;   //delay time
exec("xadoublet.exc",1);

//Outputs
varlist @genoutputs = [];
varlist @genoutputs + WORLD_MODEL_AIRFRAME_CPG_XAOUT_PSId, ..
                 WORLD_MODEL_AIRFRAME_CPG_XAOUT_PSI, ..
                 WORLD_MODEL_AIRFRAME_CPG_XAOUT_PHI, ..
                 WORLD_MODEL_AIRFRAME_CPG_XAOUT_THETA;
//Time response
exec("xanonlinear.exc",1);
uext = WORLD_ANALYSIS_NONLINEARRESP_in_UEXT;
ynl  = world_analysis_nonlinearresp_results_ynl;
```

```
  time = world_analysis_nonlinearresp_results_time;
//Results
  XPTOT  = (WORLD_MODEL_CONTROL_DATA_XPTRM + uext(:,1));
  PSId   = ynl(:,1) * world_data_r2d;
  PSI   = ynl(:,2) * world_data_r2d;
  XATOT  = WORLD_MODEL_CONTROL_DATA_XATRM + uext(:,2);
  PHI    = -ynl(:,3) * world_data_r2d;
  THETA  = ynl(:,4) * world_data_r2d;
//Save Results
  save("figure-27.sav");
parentg
//Plot
exec("figure-27.plt",1);
//EOF//
```

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